Tropical Cyclone Sensitivity:

Dynamic Interpretation and Targeted Observations

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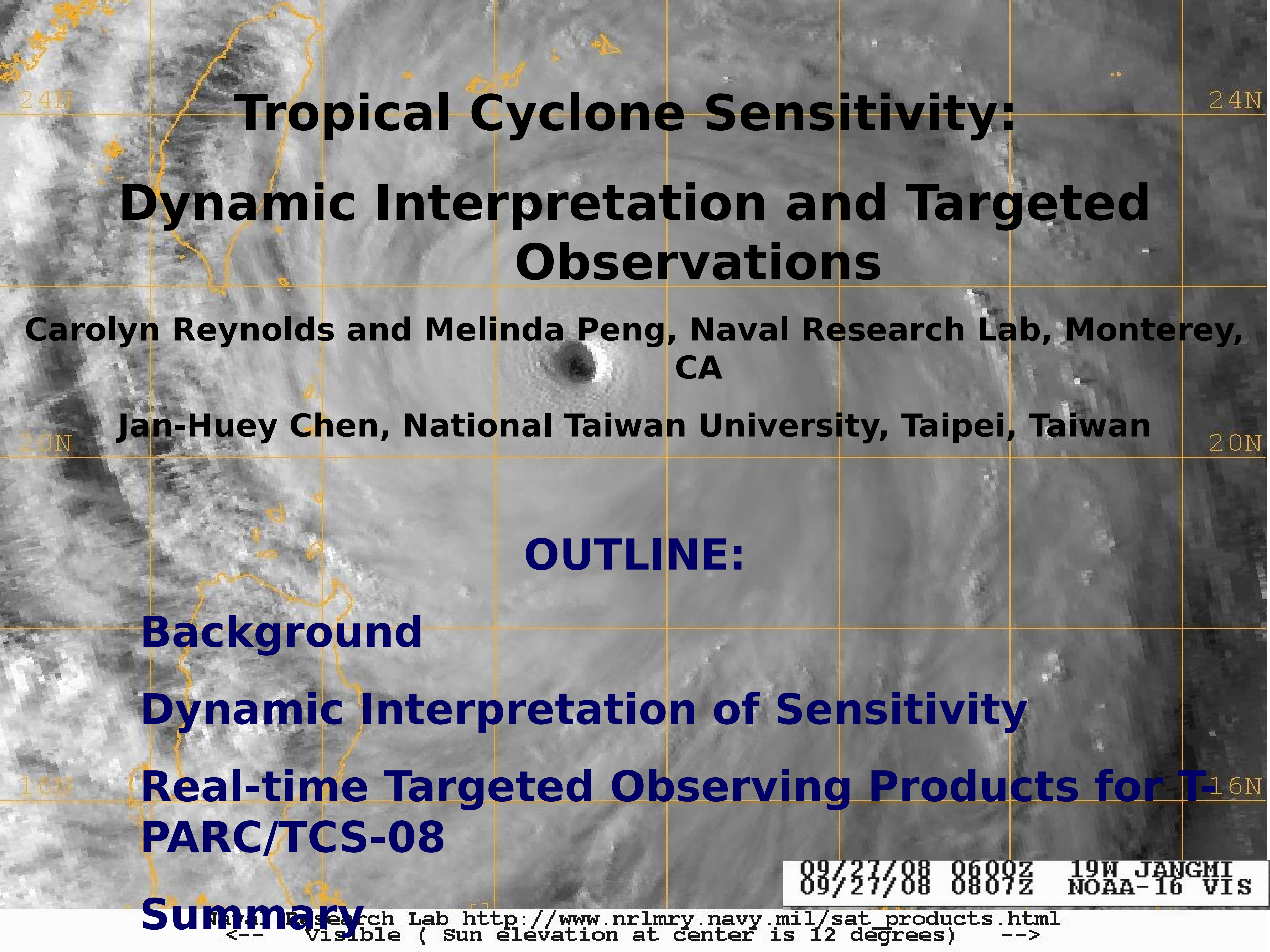
OUTLINE:

- **Background**
- **Dynamic Interpretation of Sensitivity**
- **Real-time Targeted Observing Products for T-PARC/TCS-08**
- **Summary**



BACKGROUND

- Leading Singular Vector (SV): fastest-growing initial perturbation to a particular forecast
- Previously, SVs used to examine the predictability & dynamics of midlatitude storms, and, more recently, tropical cyclones (TCs, Peng and Reynolds, 2006)
- SVs used for targeted observing, and compared to ensemble-based methods for Atlantic TCs (Majumdar et al. 2006, Reynolds et al. 2007) and Pacific TCs (Wu et al. 2008)
- Part I: Show how SVs provide information on environmental influences on TC evolution
- Part II: Show how SVs were used for targeted observing guidance during T-PARC/TCS-08

EXPERIMENTAL DESIGN

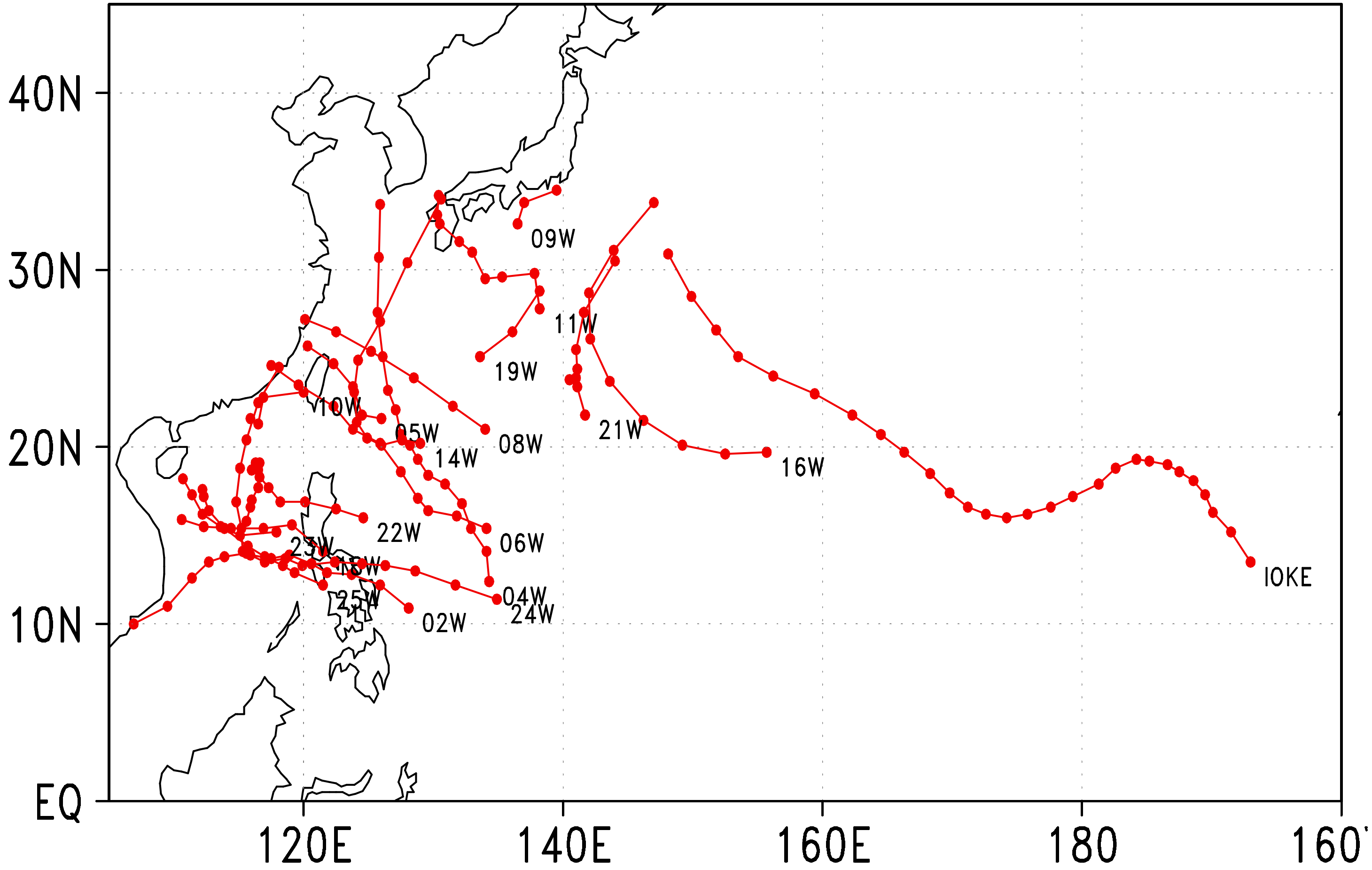
- SV calculations are produced using the Navy Operational Global Atmospheric Prediction System (NOGAPS) forecast and adjoint models.
    - T239 (0.5 deg) full-physics operational trajectory
    - T79 (1.5 deg) for SV calculation (dry)

- PART I: SVs for 2-day forecasts of western Pacific TCs of 2006.
    - Composites illustrate impact of environmental features on TC evolution
    - Case studies show how environmental impact changes during TC life-cycle

- PART II: Real-time SVs for targeted observing during T-PARC/TCS-08
    - Real-time set-up described
    - Example products shown

PART I: 2006 STORMS

SVs calculated for 72 cases from 18 Storms during 2006 (Tracks in Red)



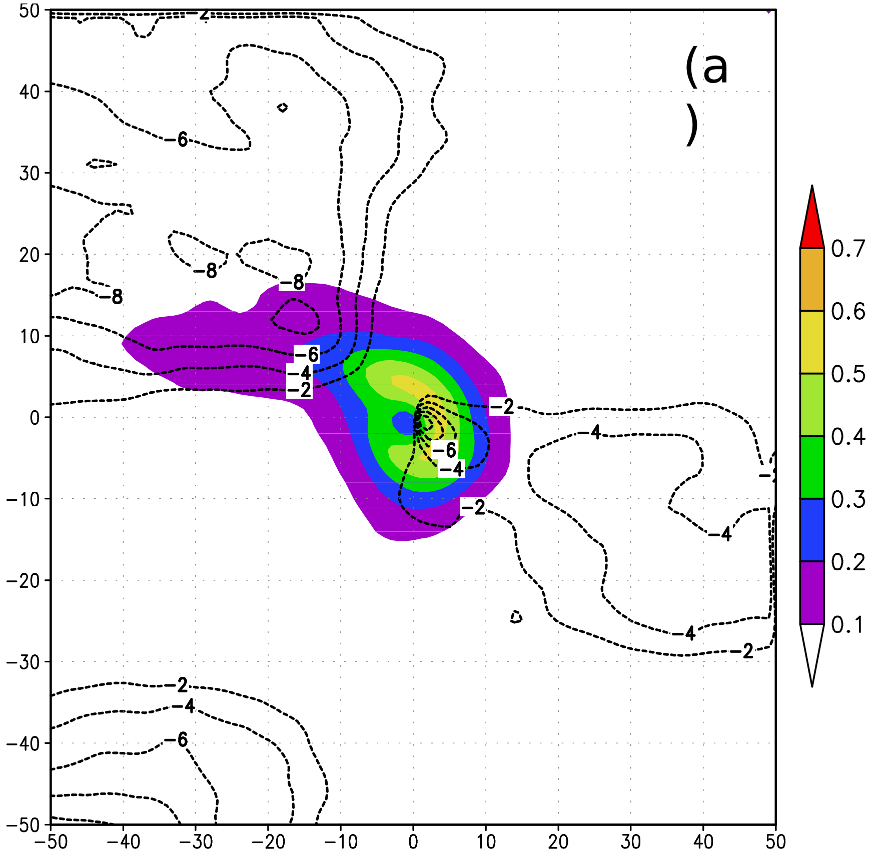
Wu, C.-C. et al: Inter-comparison of Targeted Observation Guidance for Tropical cyclones in the Western North Pacific (accepted in MWR).

Chen, J.-H. et al: Interpretation of Tropical Cyclone Forecast Sensitivity and Dynamics from a NOGAPS Singular Vector Perspective (submitted to JAS).

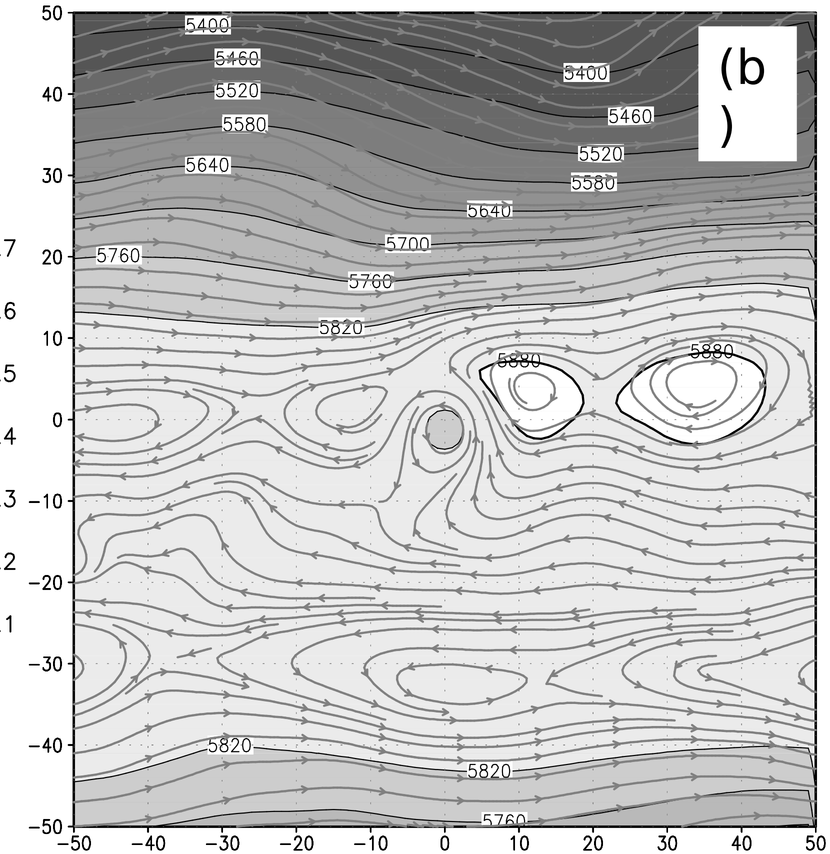
Reynolds et al: Recurving Tropical Cyclones: Singular vector sensitivity and downstream impact (accepted in MWR).

PART I: STORM-CENTERED COMPOSITES

Sensitivity and Radial Wind



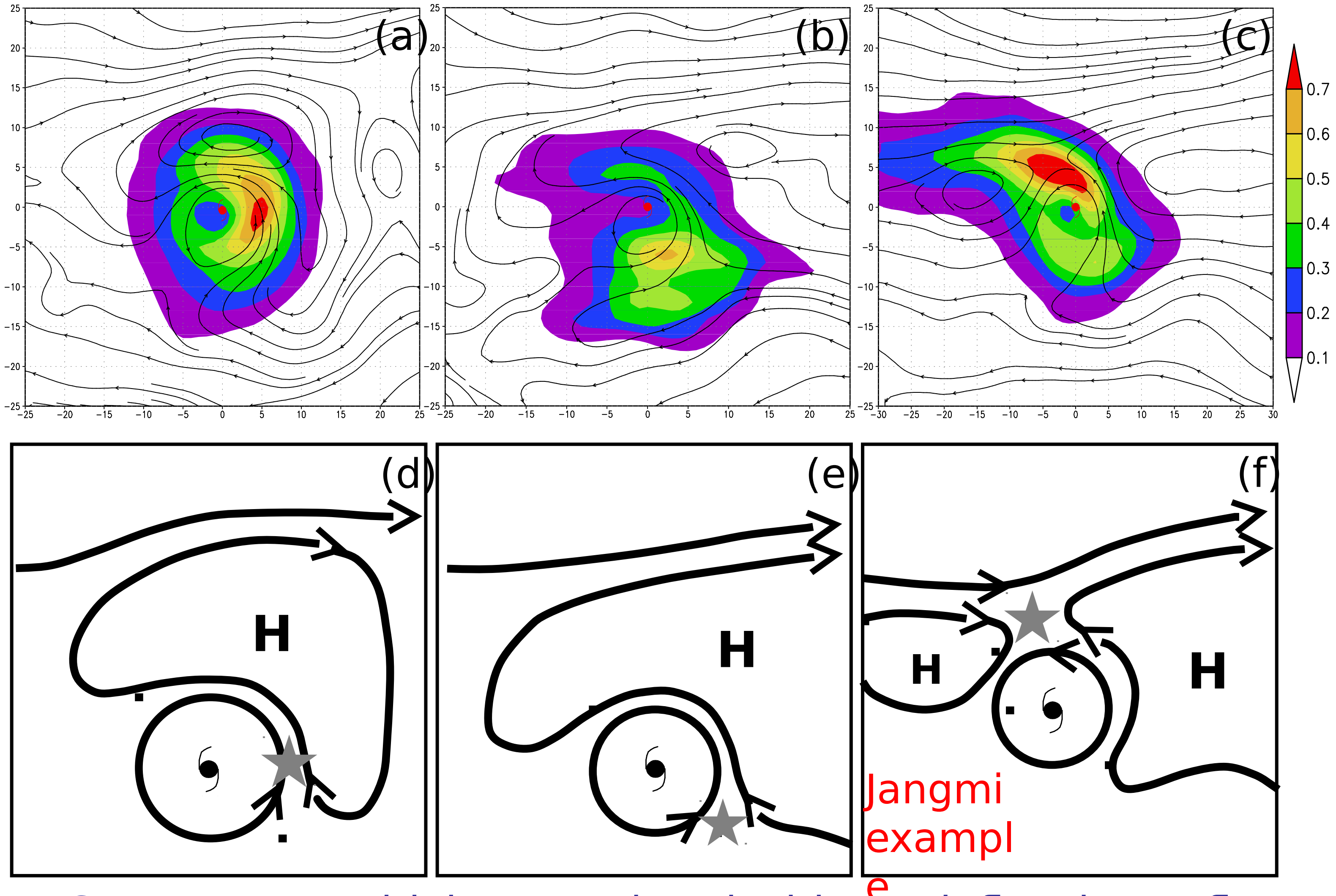
500-hPa Streamlines and Height



- SV maximum 500km from the center, where radial vorticity gradient changes sign. Perhaps associated with vortex Rossby wave instability (Peng and Reynolds 2006).
- SVs collocated with regions of flow toward the storm (steering flow, influence of upstream trough).

PART I: STORM-CENTERED COMPOSITES

Weak Inflow Groups



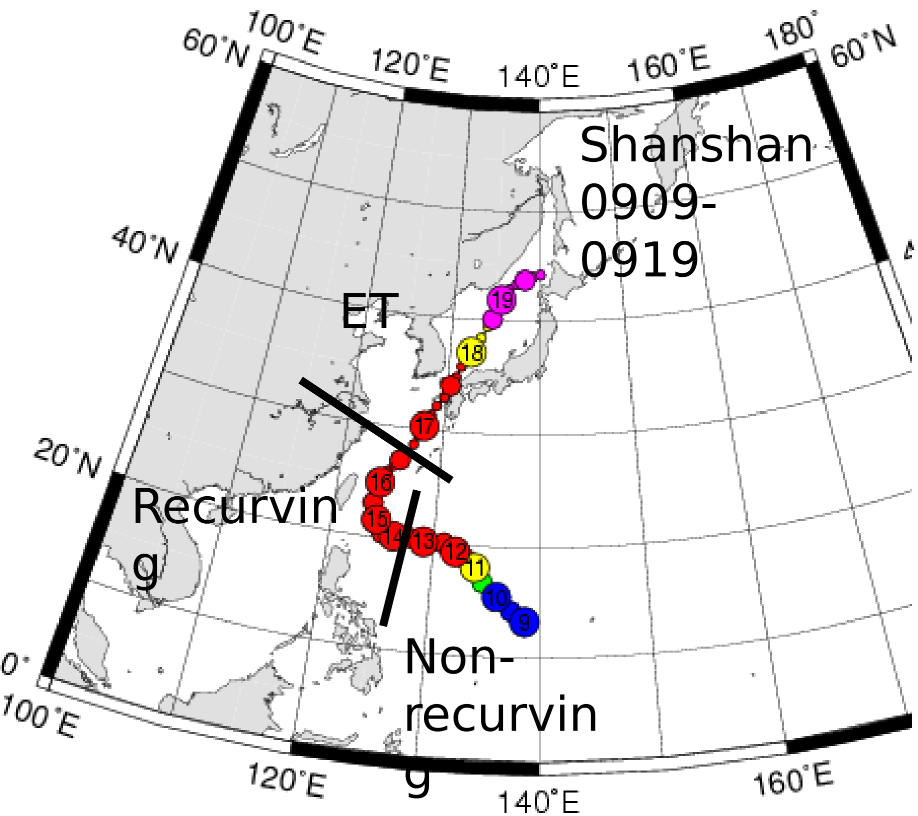
– Strongest sensitivity associated with weak flow in confluence regions between systems. Uncertainty associated with how these systems interact (e.g., which system dominates) can lead to forecast errors.

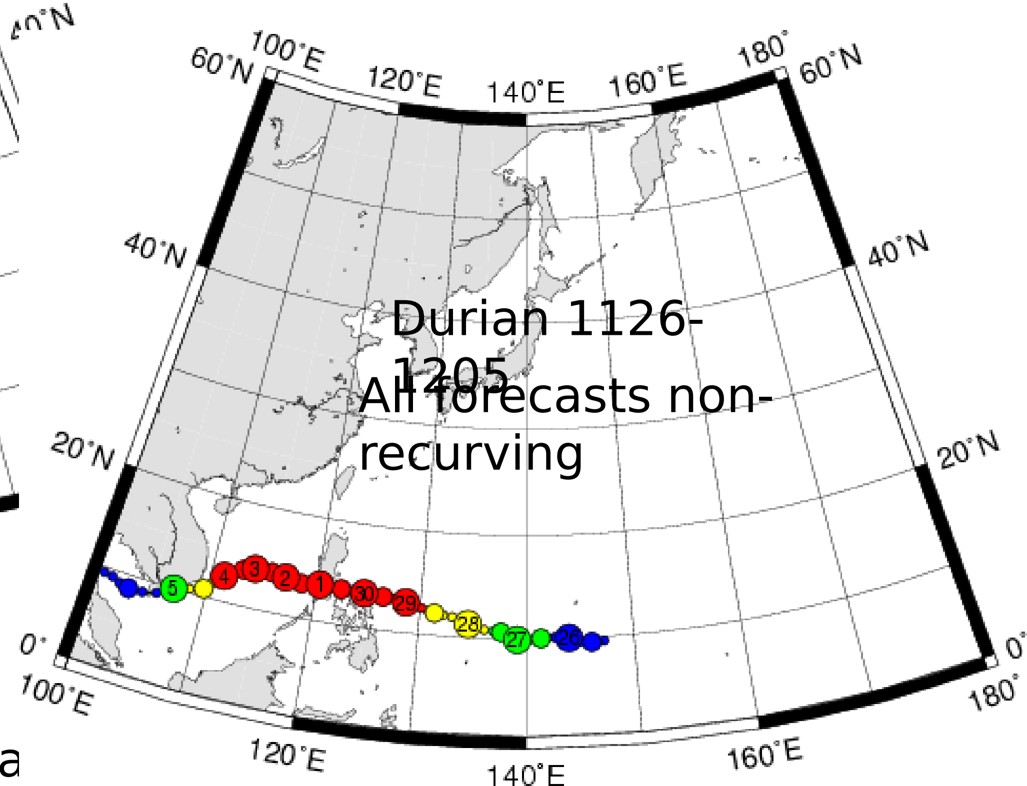
PART I: RECURVATURE CASES

Focus on recurvature period (subjectively determined). Examples for two storms shown here.

From Digital Typhoon Website:

http://agora.ex.nii.ac.jp/digital-typhoon/



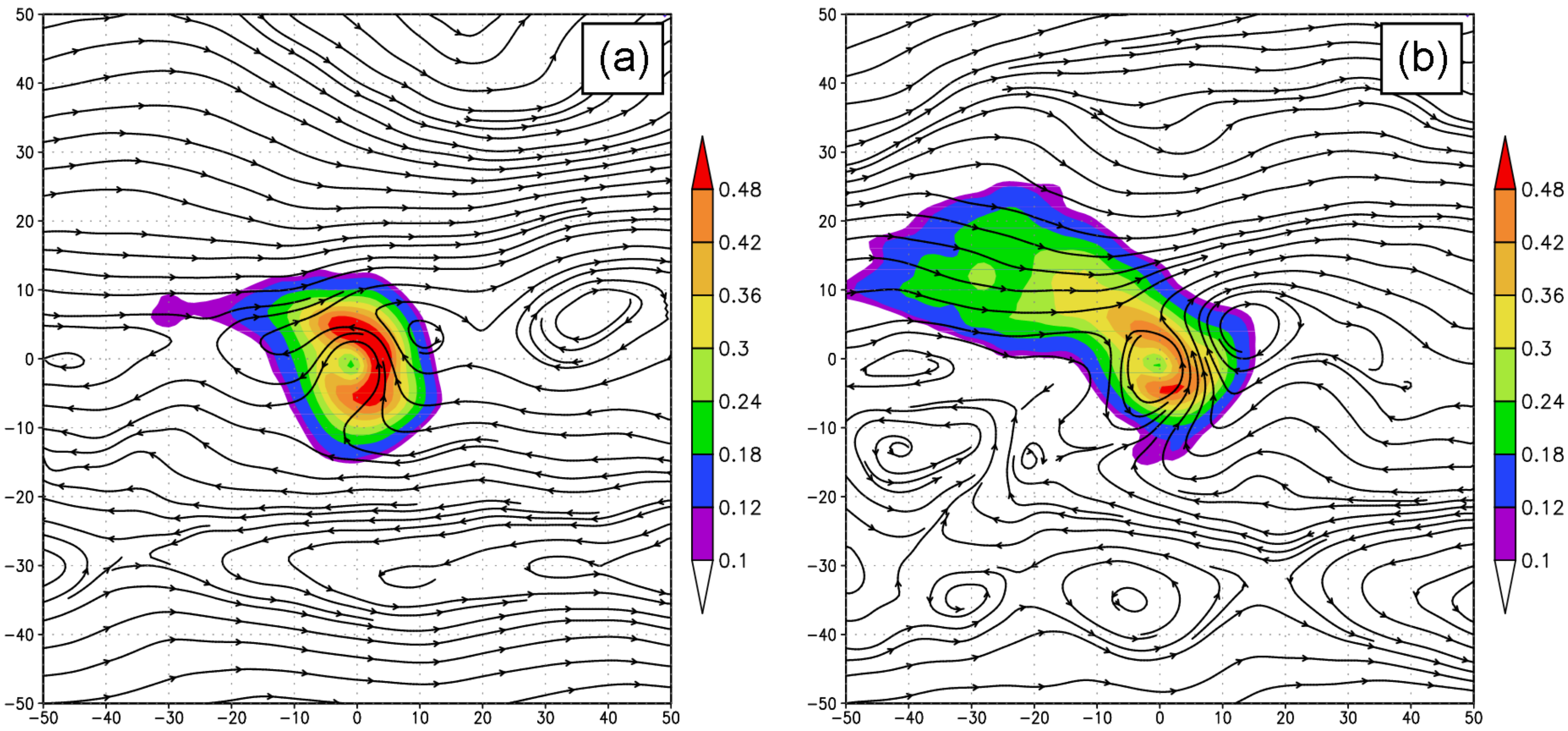


USPACOM Tropica

PART I: INITIAL SV COMPOSITES ABOUT STORM CENTER

Vertically-integrated SV total energy (shading), 500-hPa streamlines (contours)

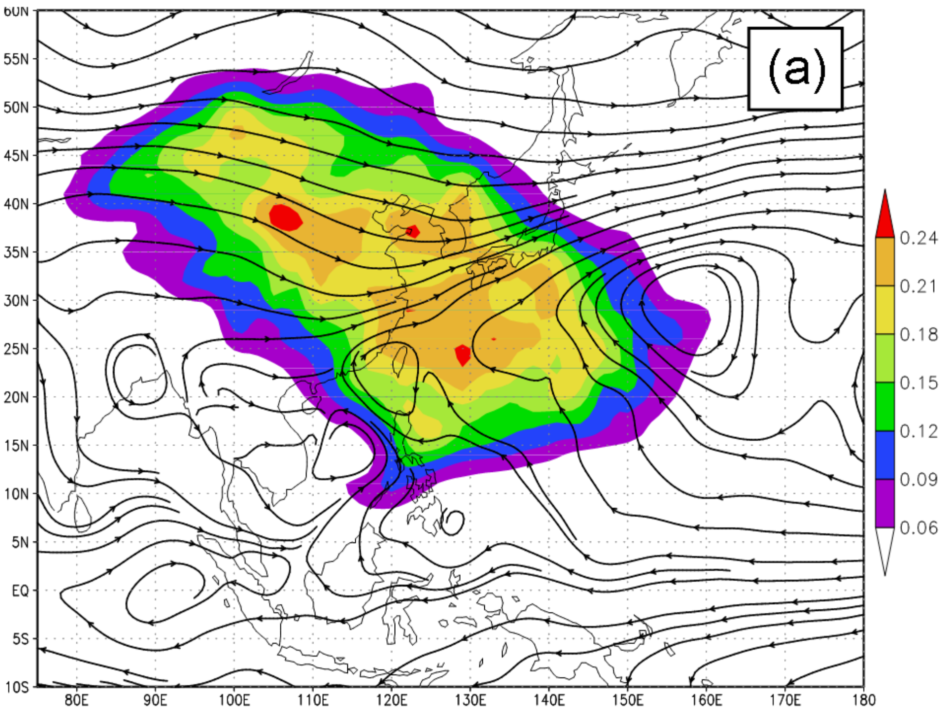
50 NON-RECURVING CASES **22 RECURVING CASES**



– Sensitivity to the north-west of the storm enhanced during recurvature

PART I:
SENSITIVE LOCATIONS FOR RECURVING STORMS

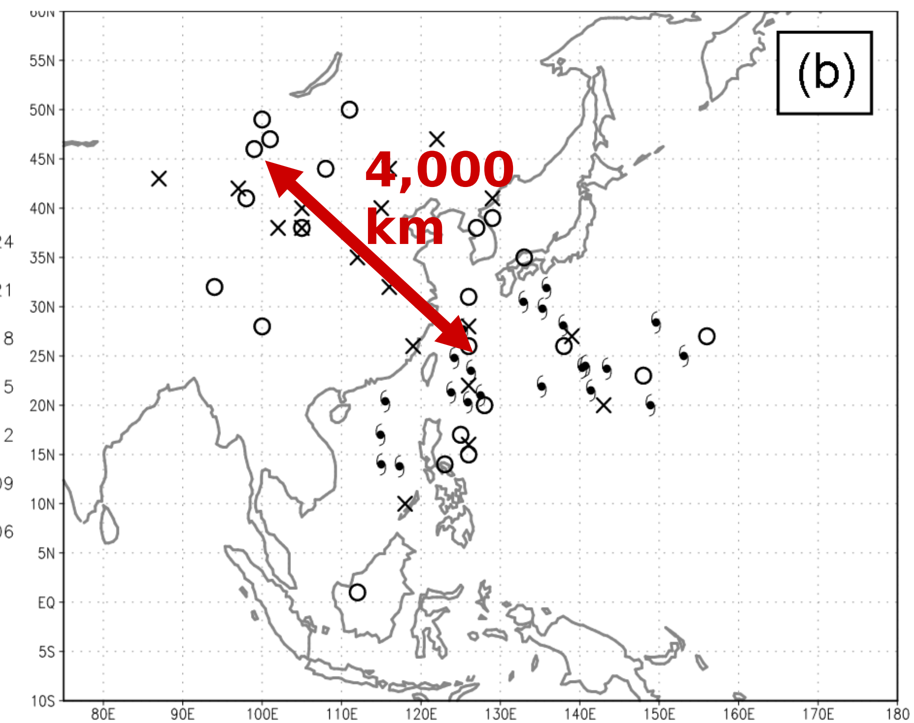
Average SV sensitivity during recurvature



Storm symbol: TC locations

o : Primary initial SV max locations

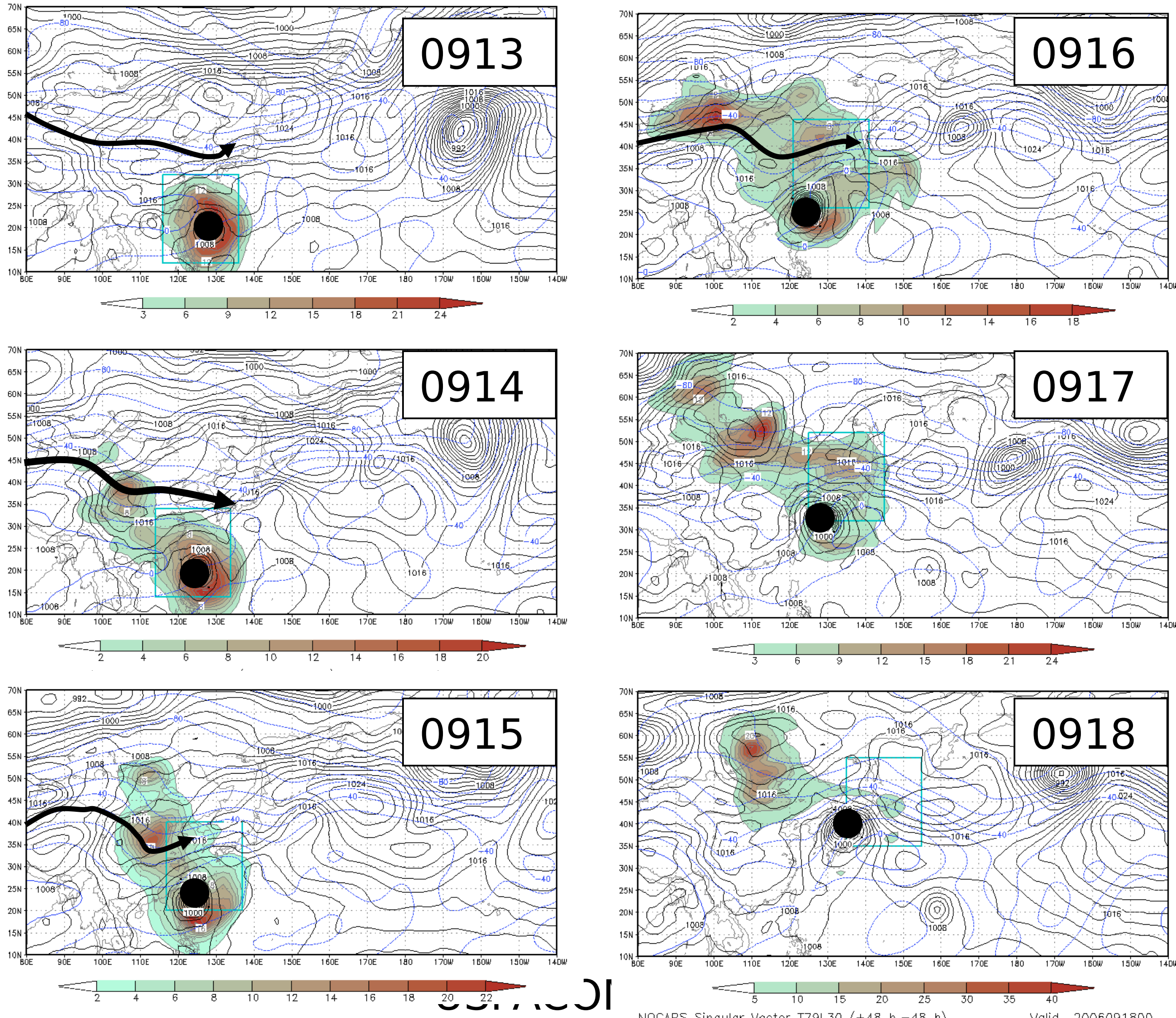
x : Secondary initial SV max



- SV sensitivity for 48-h forecasts during recurvature can be significantly far upstream, often over Asia

PART I: CASE STUDY: SHANSHAN

SV Total Energy during Shanshan's life cycle (shading). Analyzed SLP (black) and 200-hPa streamfunction (blue).



Typical Sensitivity Patterns:

Early stage: concentrated around storm

Recurvature: associated with a trough to the north-west

Extratropical Transition: patterns are very complex

PART II: THORPEX Pacific Asian Regional Campaign (TPARC)
Tropical Cyclone Structure 08 (TCS-08)

Observe TCs and their environment from genesis to extratropical transition. Aug-Oct 2008; 9 nations; 4 aircraft (lidar, Eldora radar, dropsondes), driftsondes, rapid-scan satellite obs, off-time radiosondes, buoys.

Targeted Observing Objective: Take additional observations in regions where they are most likely to improve forecasts

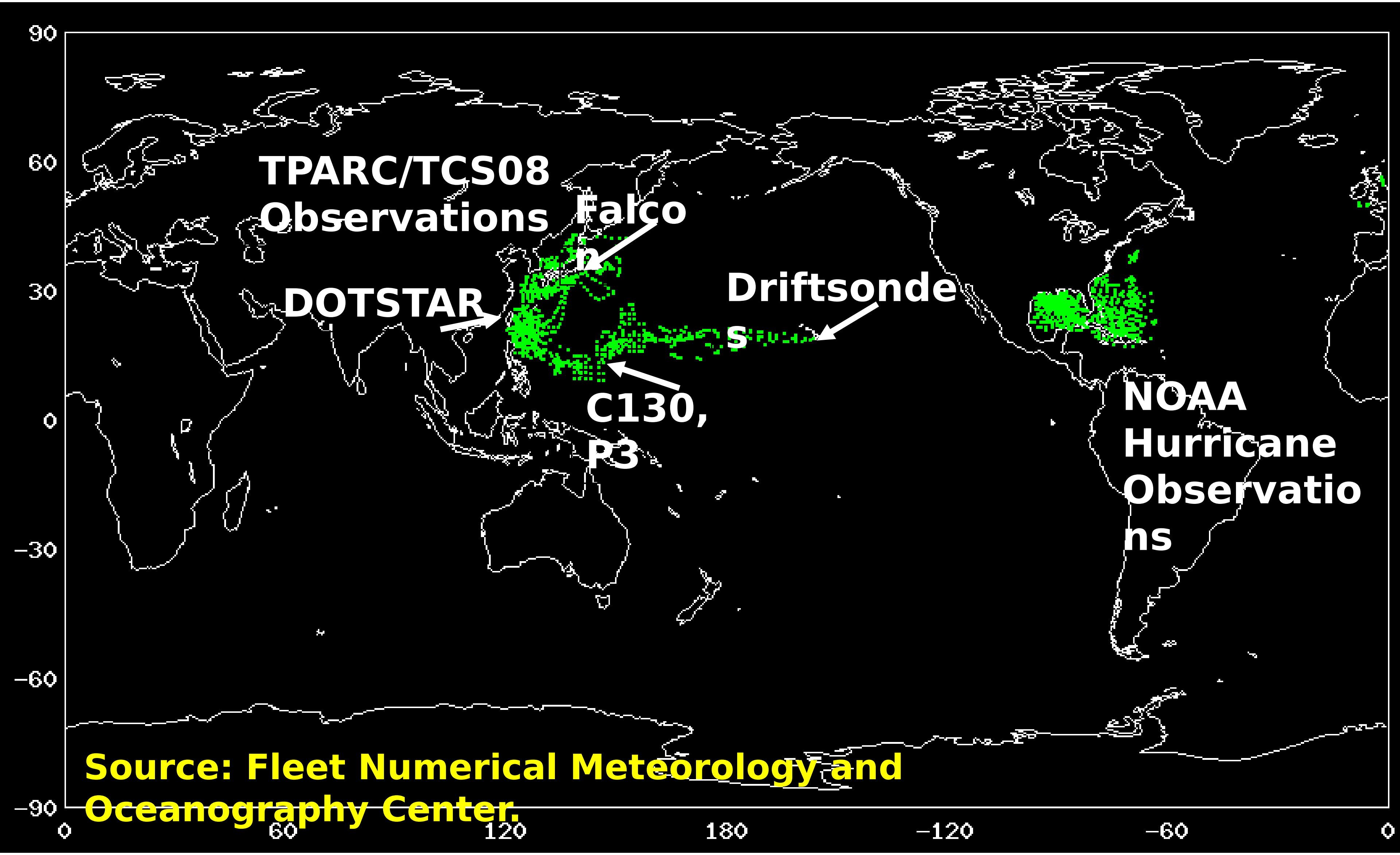
Ensemble-based and adjoint-based guidance provided from operational, research, and academic centers

NRL real-time products:

- Navy Operational Global Atmospheric Prediction System (NOGAPS) Singular Vectors

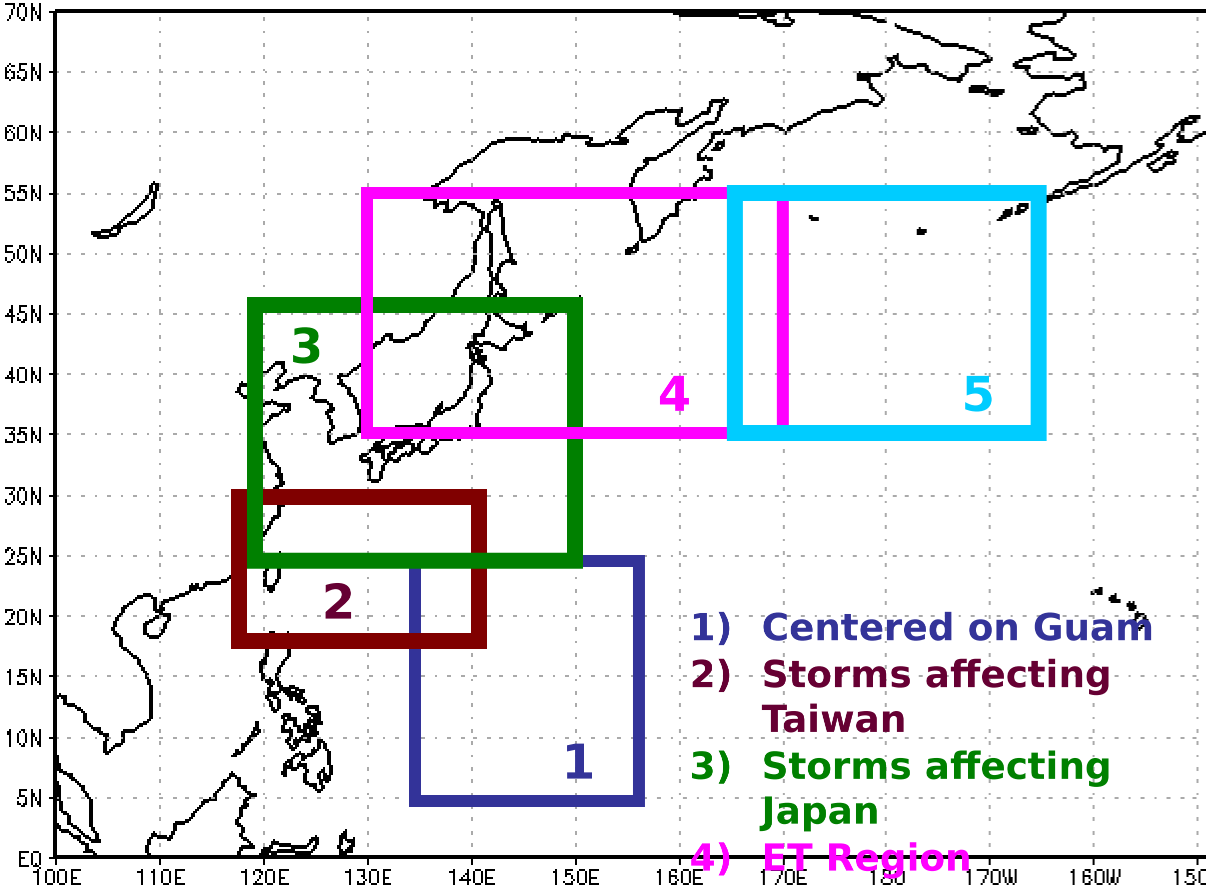
- Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS®) Adjoint

PART II: DROPSONDE and DRIFTSONDE OBSERVATIONS: SEPT 2008



PART II: NOGAPS SVs- 5 Fixed Regions, Twice Daily

- **T79L30 adjoint/TLM resolution**
- **T239L30 (operational) trajectory**
- **Dry Total Energy norm**



1) **Centered on Guam**
2) **Storms affecting Taiwan**
3) **Storms affecting Japan**
4) **ET Region**
5) **Central North Pacific**

Details:

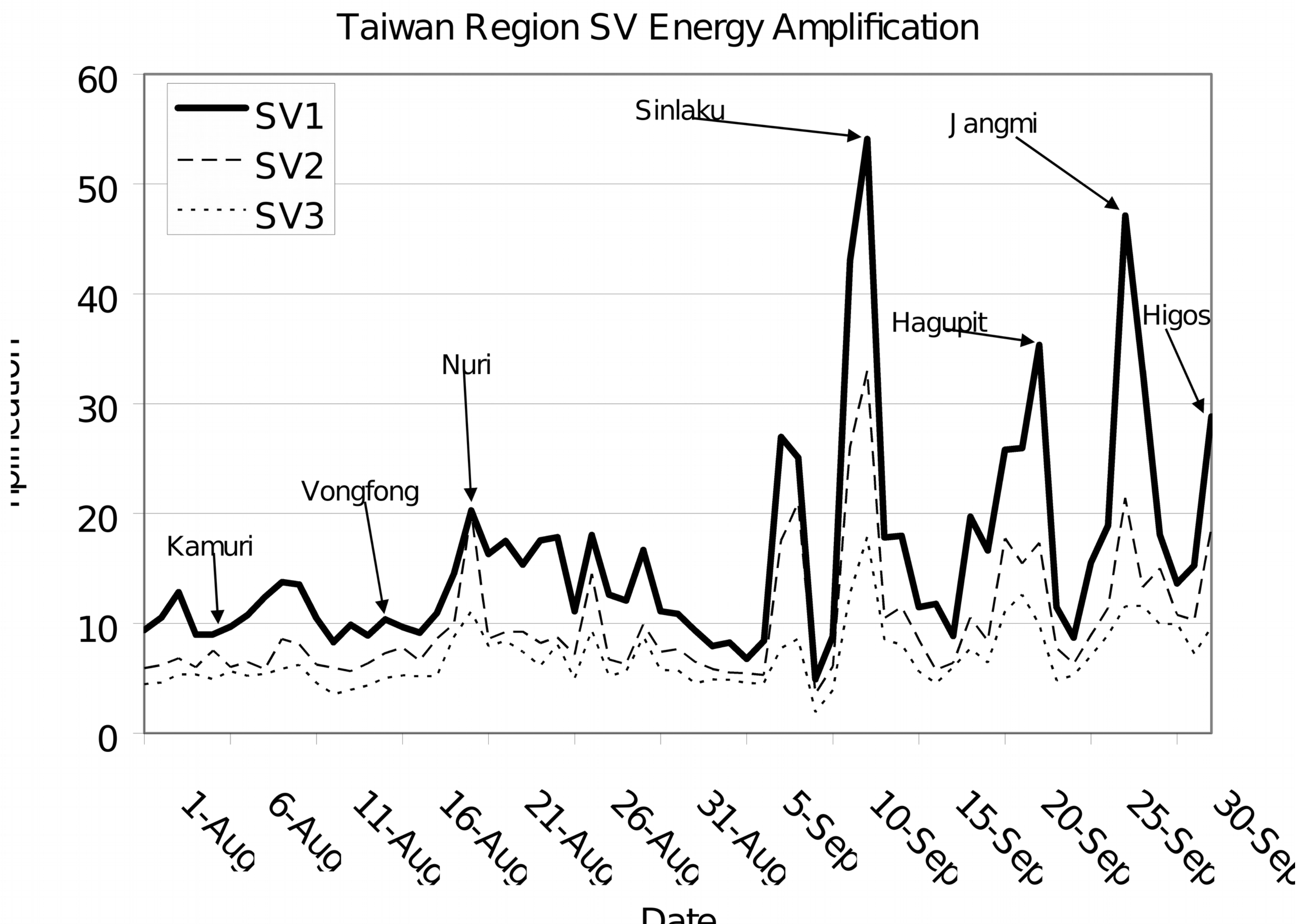
- **48-h lead-time off 00Z run (available 09 UTC, 39-h prior to target time)**
- **60-h lead-time off 12Z run (available 21 UTC, 51-h prior to target time)**
- **48-h optimization times for all regions except 72-h opt time for North Pacific Region**

During high-interest periods:

- **24-h lead time and 36-h lead time products**
- **Flow-dependent verification regions**

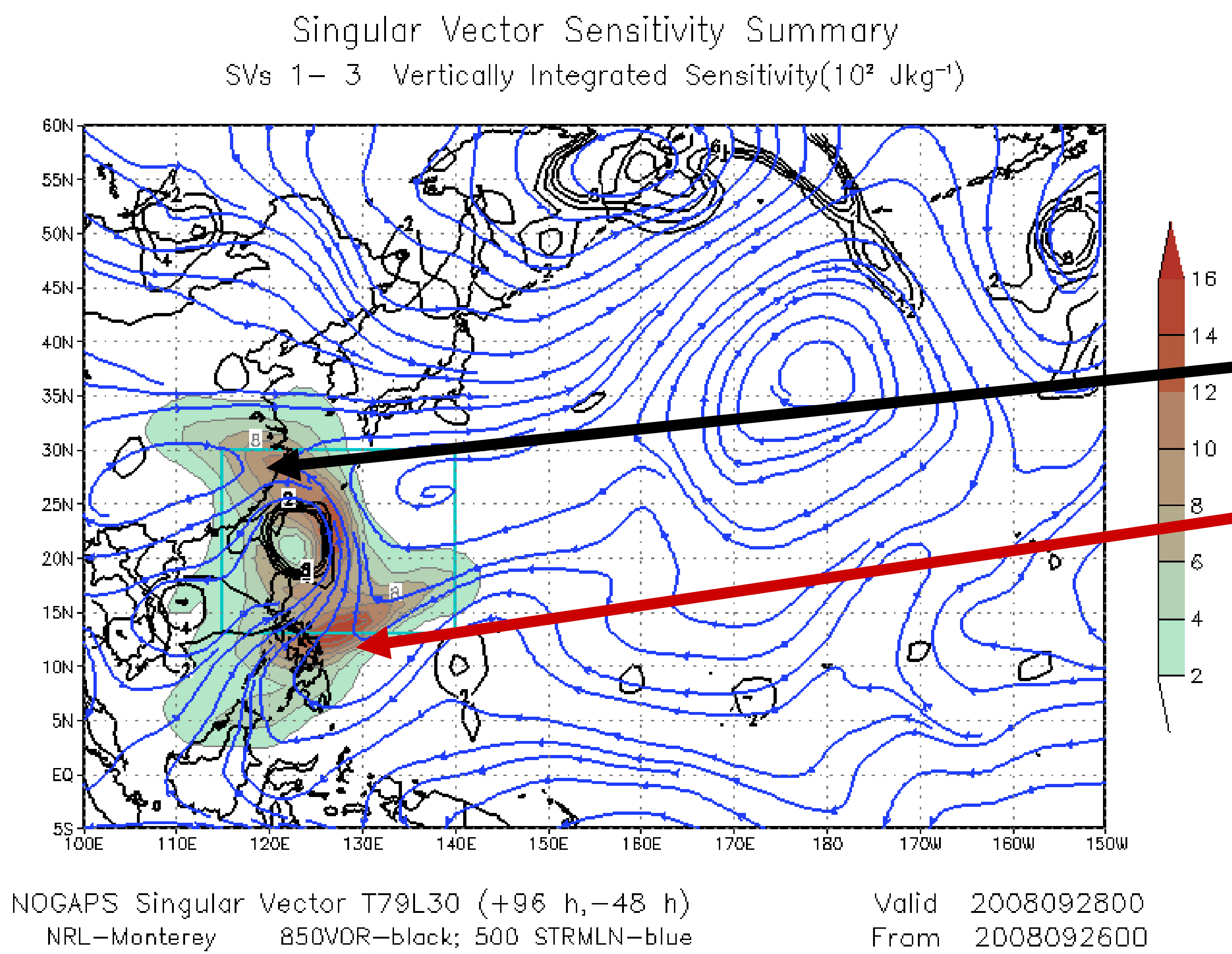
PART II: Amplification Factors for Taiwan Region

SVs growth larger when Typhoons are within region



PART II: NOGAPS SVs for JANGMI (2008092800)

500-hPa streamlines help relate sensitivity to steering dynamics

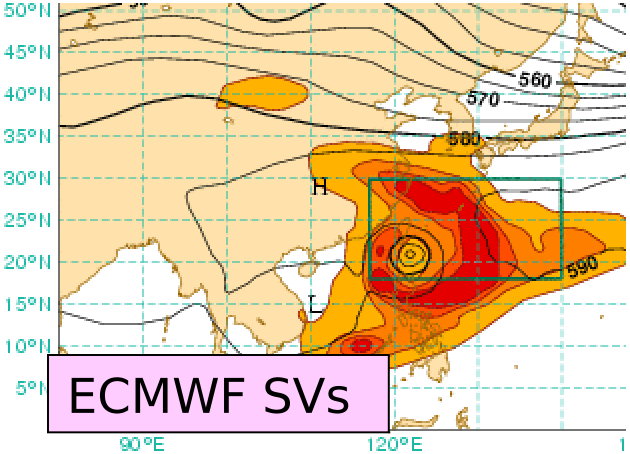


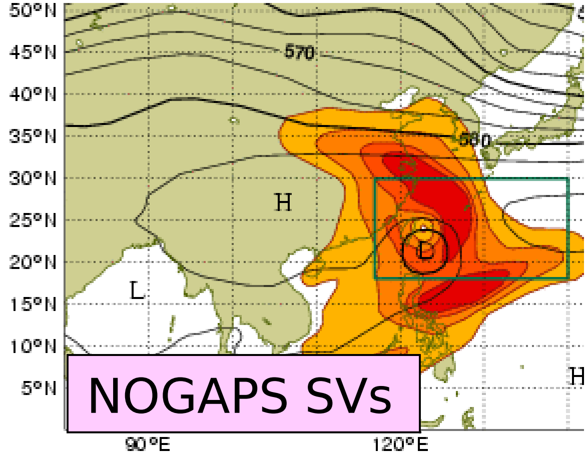
SVs related to TC dynamics.

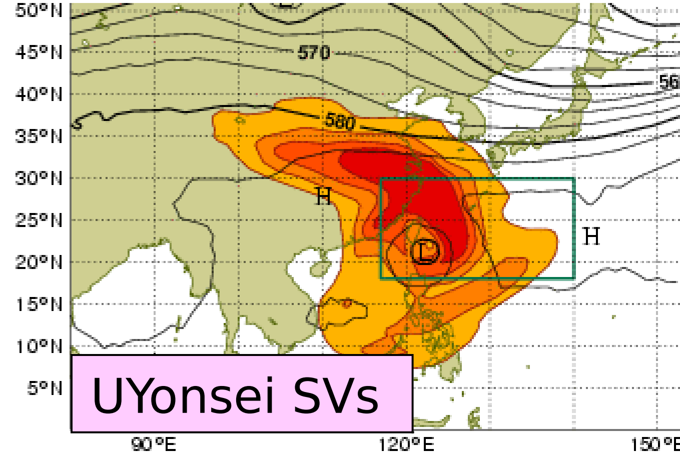
Associated with <u>weakness in the ridge</u> on the north side of storm and <u>peripheral high</u> to southeast of storm.

PART II: NOGAPS SVs on ECMWF/UKMO PREVIEW SYSTEM

Uniform graphics facilitated comparison

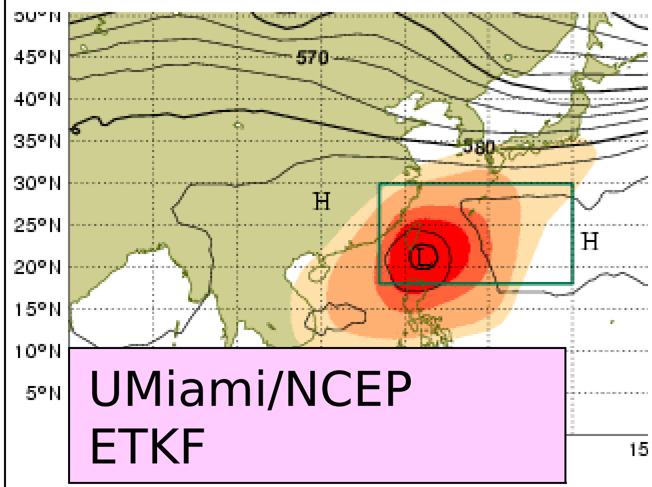


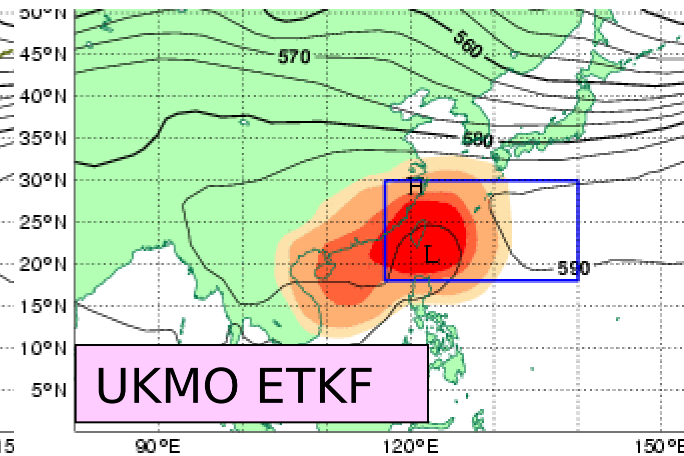


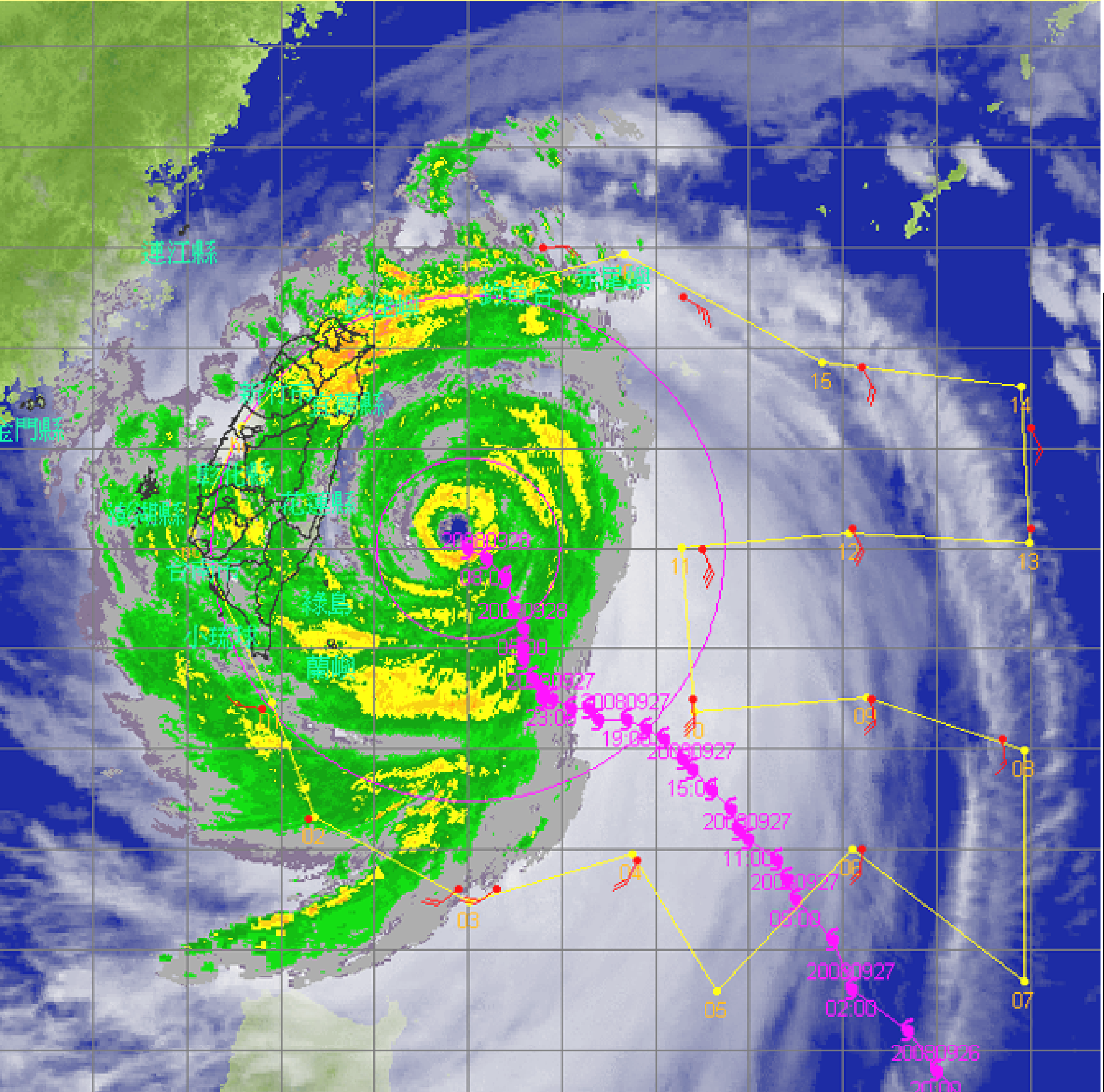


Targets for Jangmi, 2008092800. Sensitive regions from southeast to north of storm.

Note similarities among SV products (top row) and among ensemble (ETKF) products, bottom







DOTSTAR OBSERVATIONS FOR JANGMI, 2008082800.

TC track (pink) and DOTSTAR flight (yellow) superposed on satellite and radar image of TC Jangmi.

Observations around the storm, plus additional obs in sensitive region to east and southeast of storm.

Additional observations taken north-east of TC by the Falcon.

Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region: http://typhoon.as.ntu.edu.tw/DOTSTAR/en/

SUMMARY:

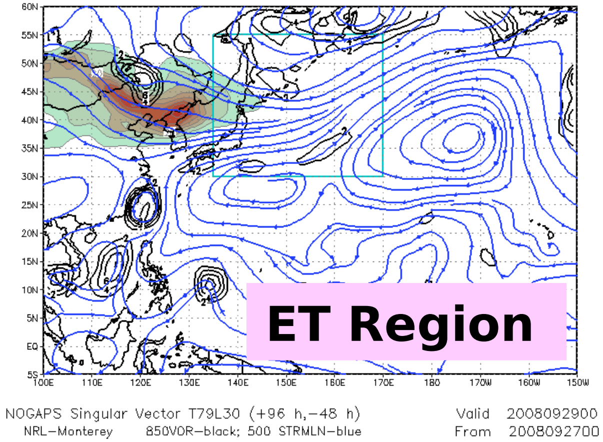
NOGAPS SVs for DYNAMICS AFFECTING TC EVOLUTION:

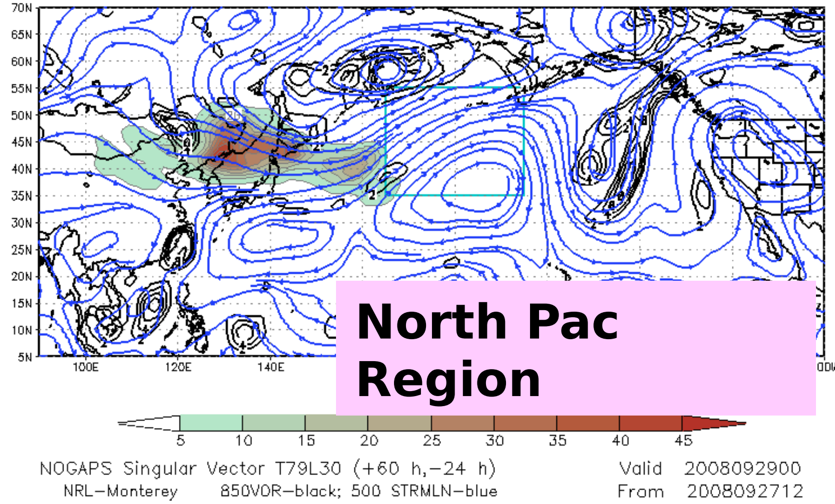
- **Largest sensitivity associated flow towards the storm**
- **Large sensitivity associated with confluence regions**
- **Recurving storms had large sensitivity to northwest and large downstream impacts**

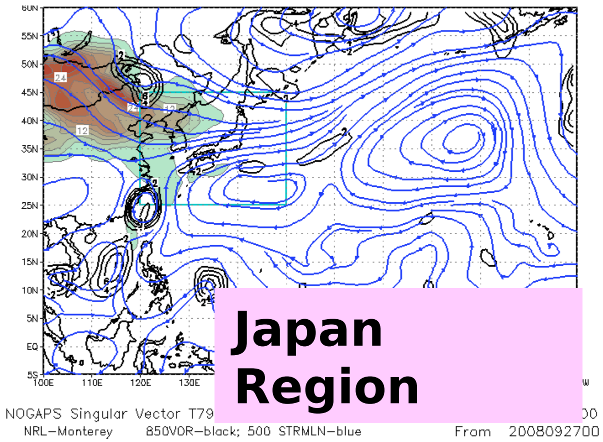
NOGAPS SVs for T-PARC/TCS-08:

- **Five fixed region SVs provided twice daily**
- **Having many products available proved useful; discussions led to targeting consensus**
- **Often possible to relate position of sensitivity to general dynamic understanding of steering mechanisms**
- **Ongoing data denial experiments will help**

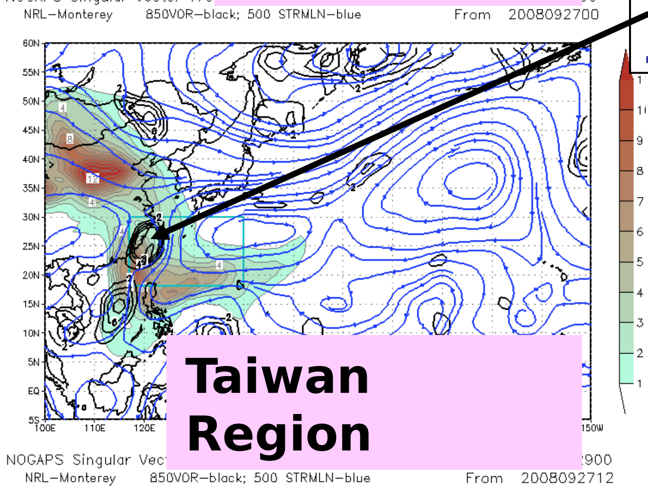
EXTRA SLIDES

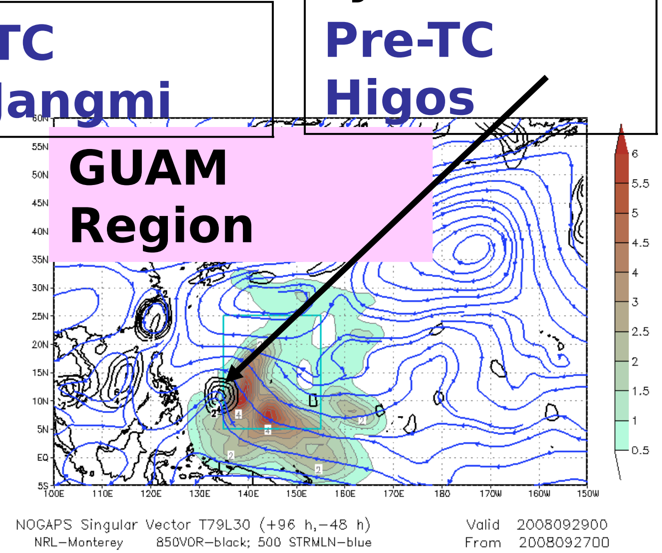




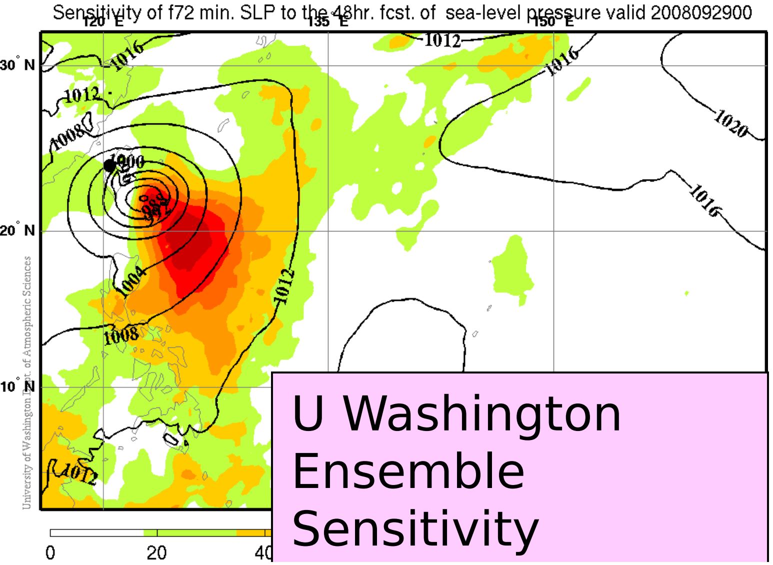


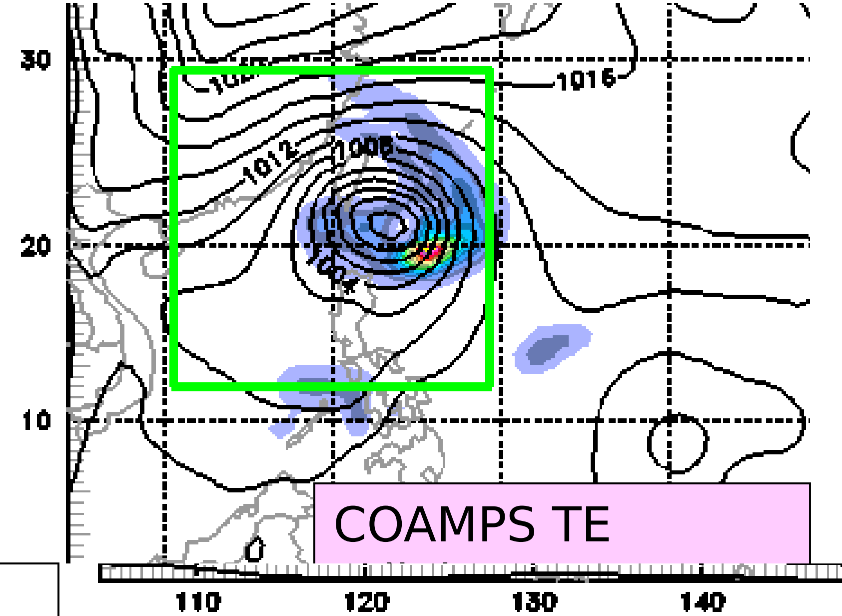
NOGAPS SV Examples for Targets on 2008092900: SV total energy (shaded) with 500-hPa streamlines (blue) and 850-hPa vorticity (black).

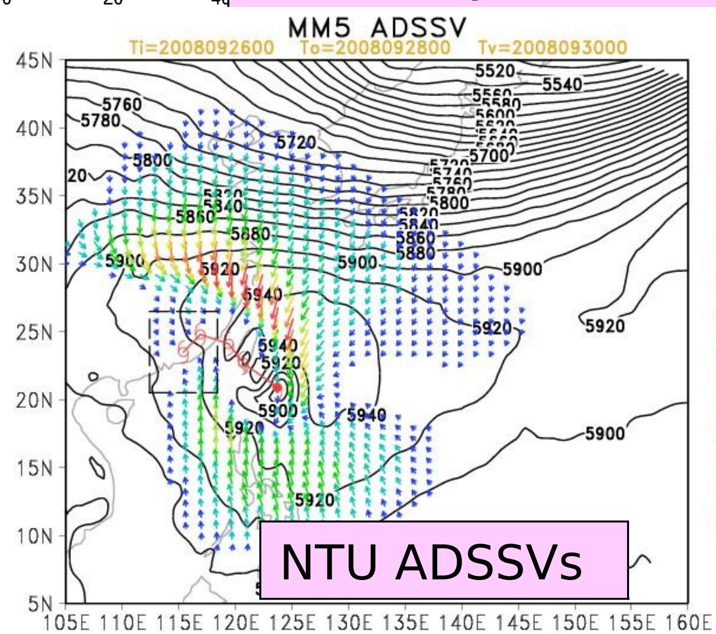




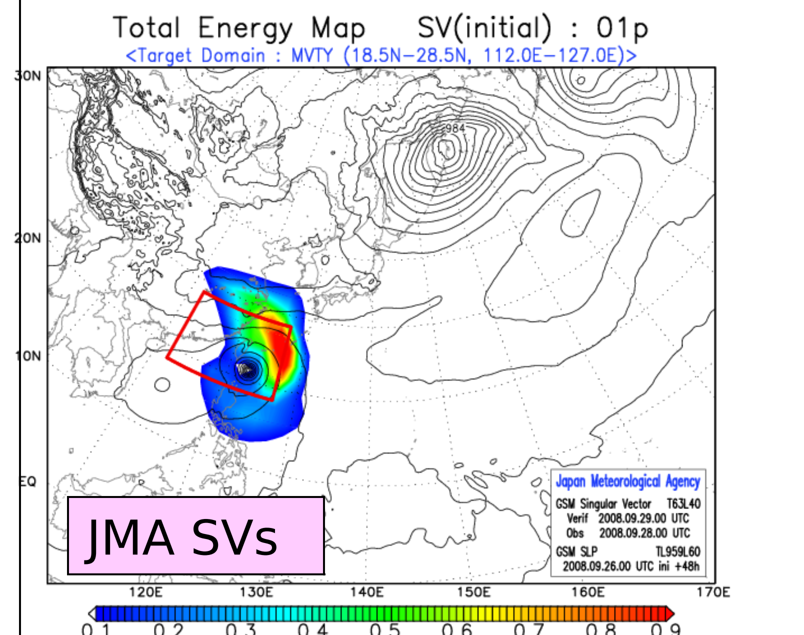
PART II: MANY OTHER PRODUCTS AVAILABLE



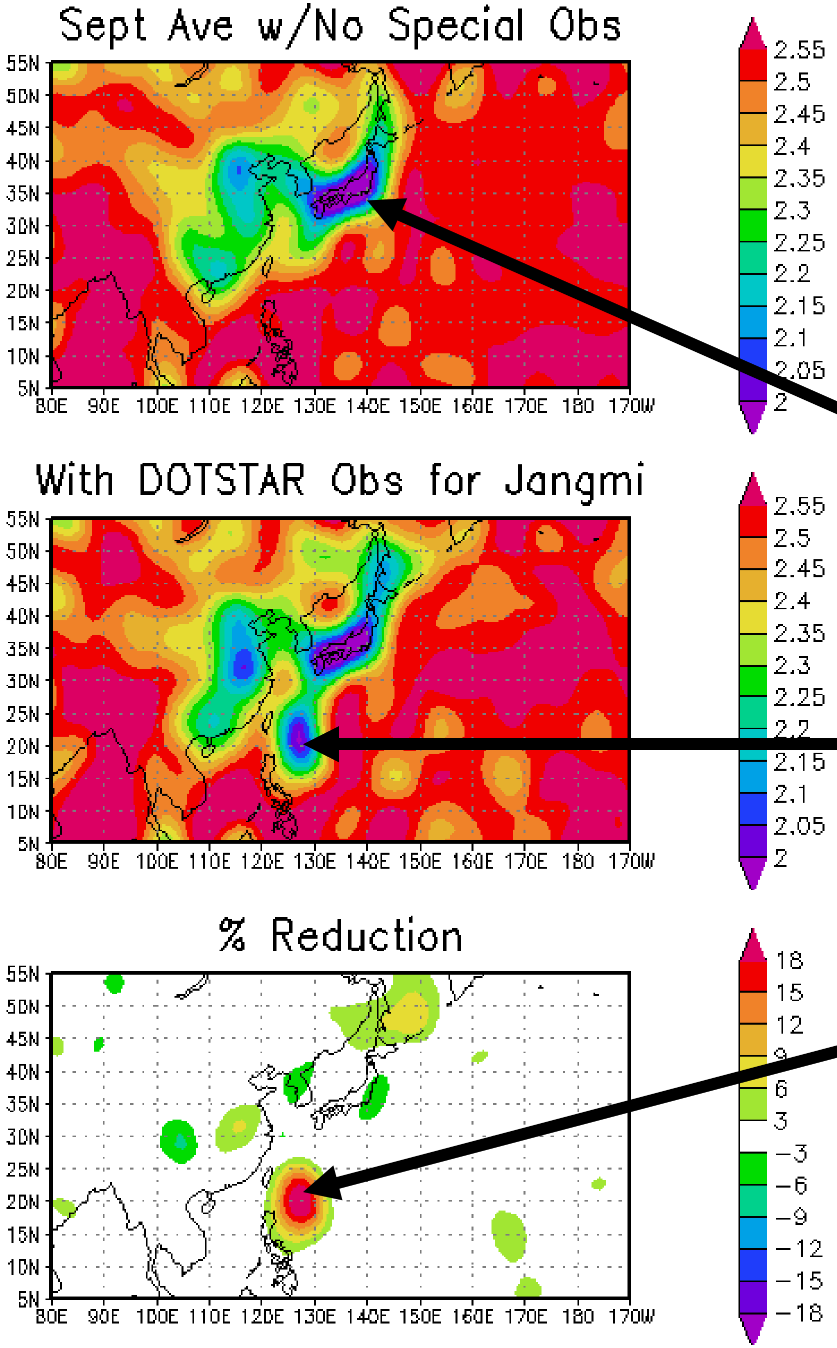




Targets for Jangmi, 2008082800 Sensitivity primarily southeast to northeast of storm.



NAVDAS (3DVAR) Analysis Error STDV Estimate for 500-hPa wind (m/s)



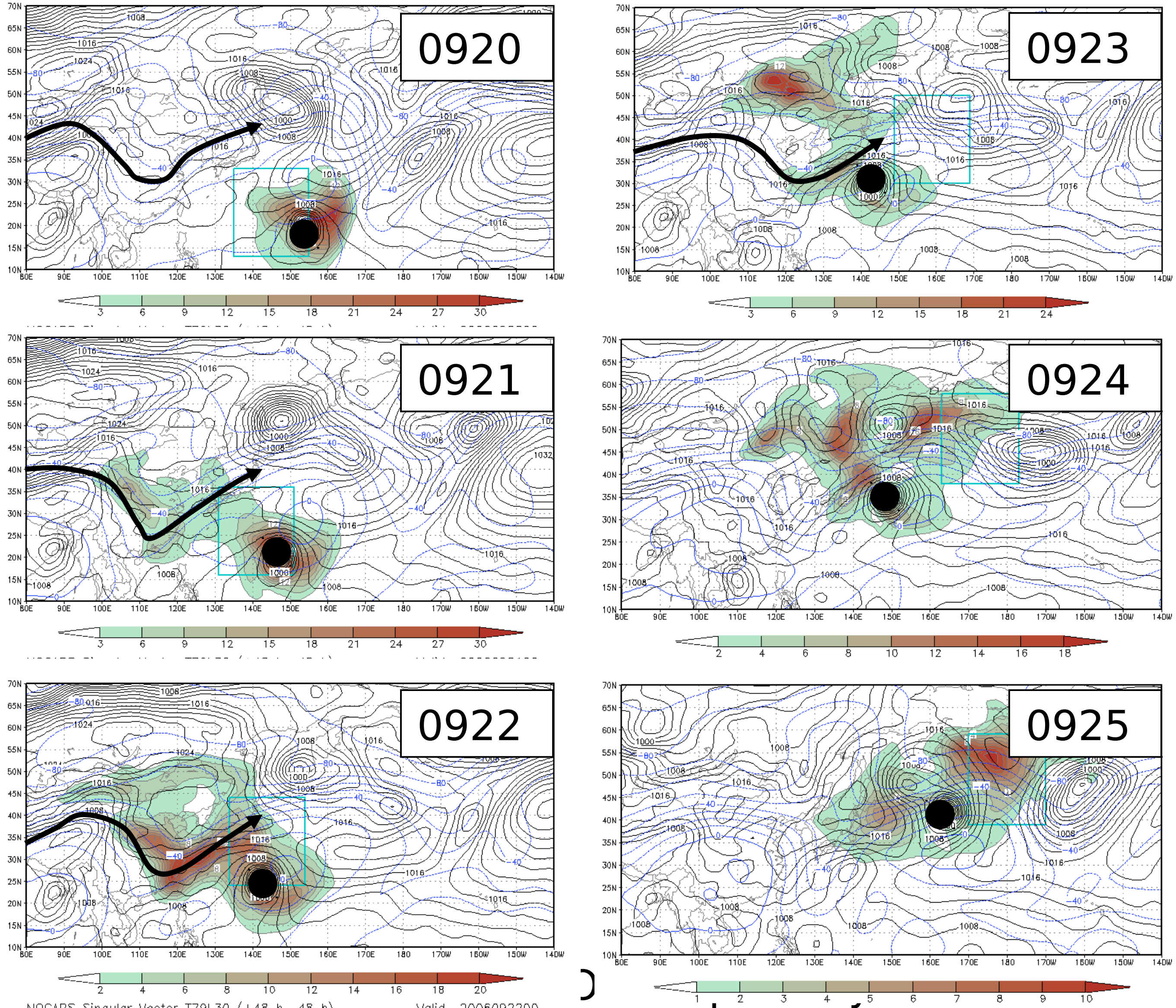
September values for days with no special obs show relatively low error values over Japan (high-density observing network).

With DOTSTAR Observations for TC Jangmi, low error values extend to area east of Taiwan.

NAVDAS estimates significant reduction in analysis error (close to 20%) in vicinity of Jangmi.

PART I: CASE STUDY: YAGI

SV Total Energy during Yagi’s life cycle (shading). Analyzed SLP (black) and 200-hPa streamfunction (blue).



Typical Sensitivity Patterns:

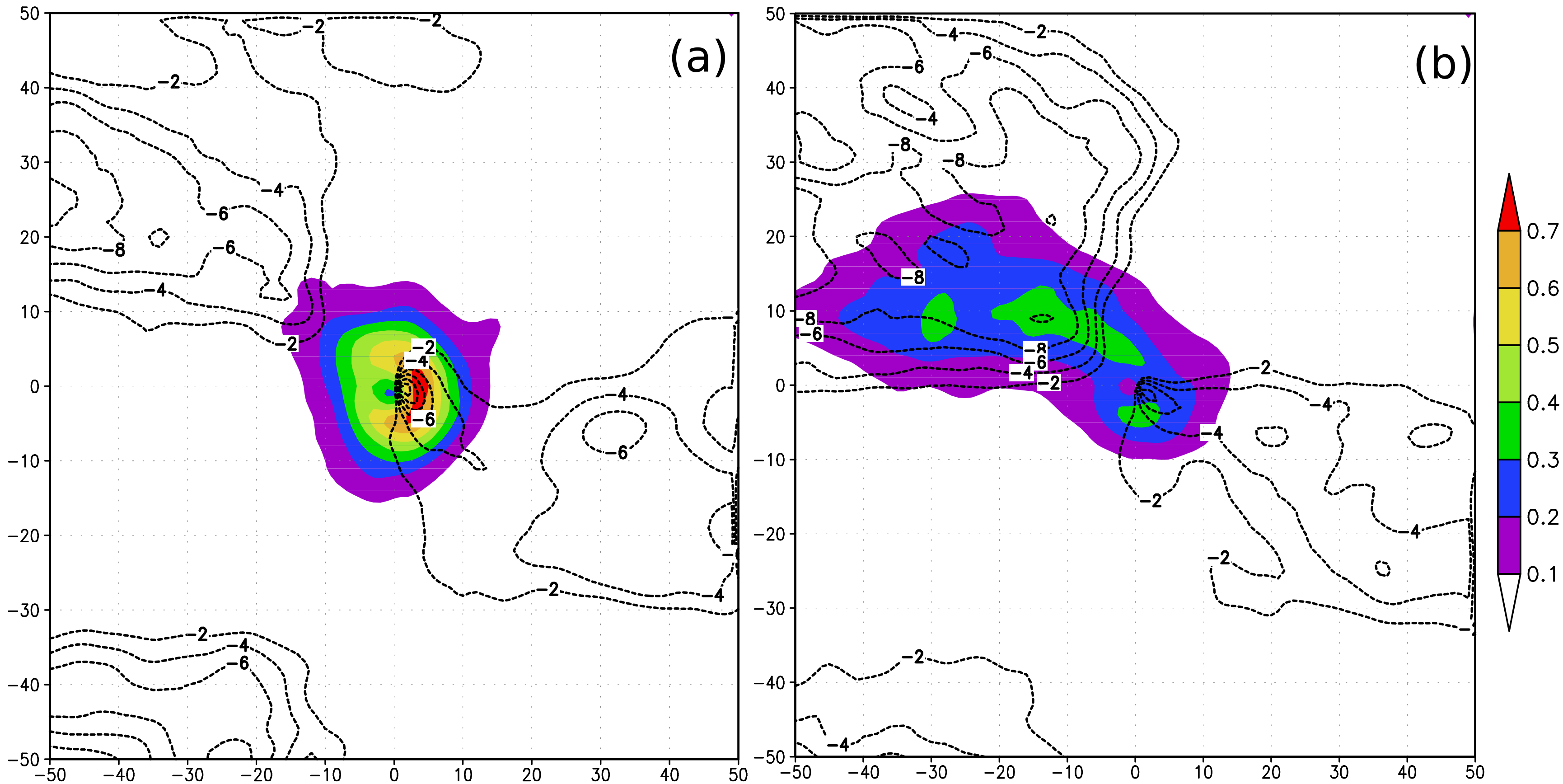
Early stage: concentrated around storm

Recurvature: associated with a trough to the north west

Transition: patterns very complex and case-dependent

PART I: STORM-CENTERED COMPOSITES

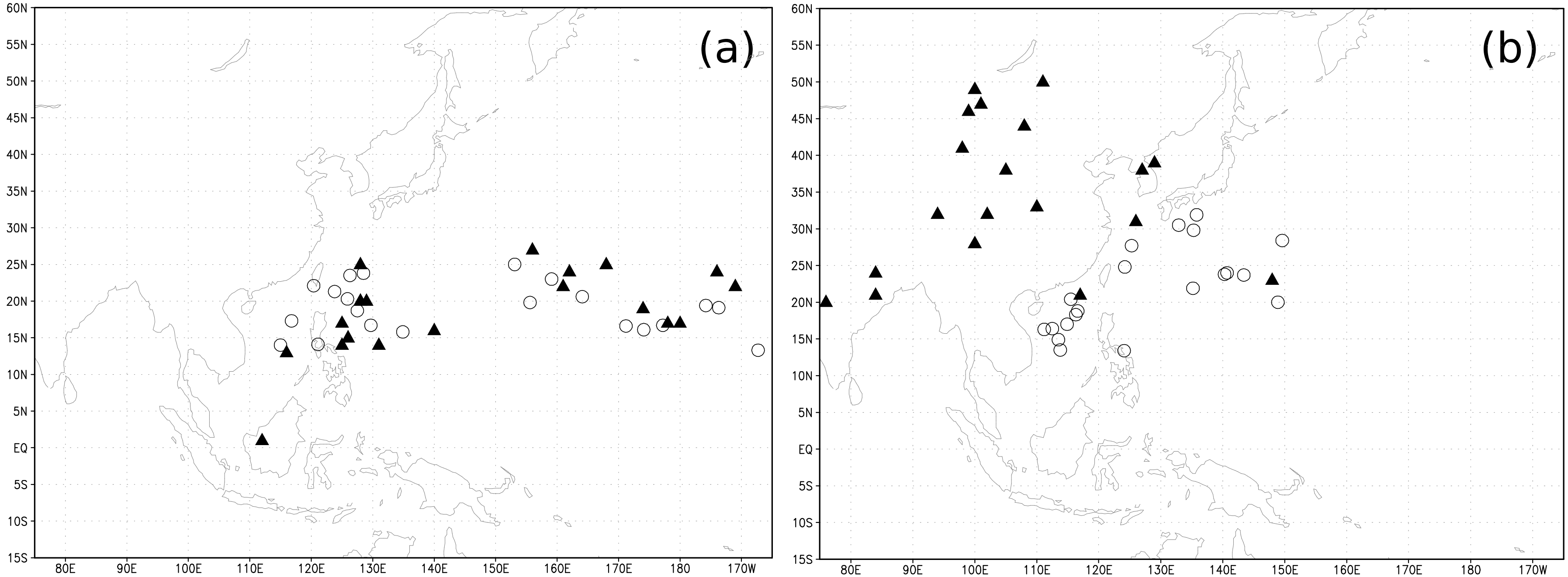
NEAR INFLOW GROUP　　　REMOTE INFLOW GROUP



- Separating storms into “near inflow” and “remote inflow” groups shows that remote sensitivity associated with strong flow towards the storm to the northwest

PART I: STORM AND SENSITIVITY LOCATIONS

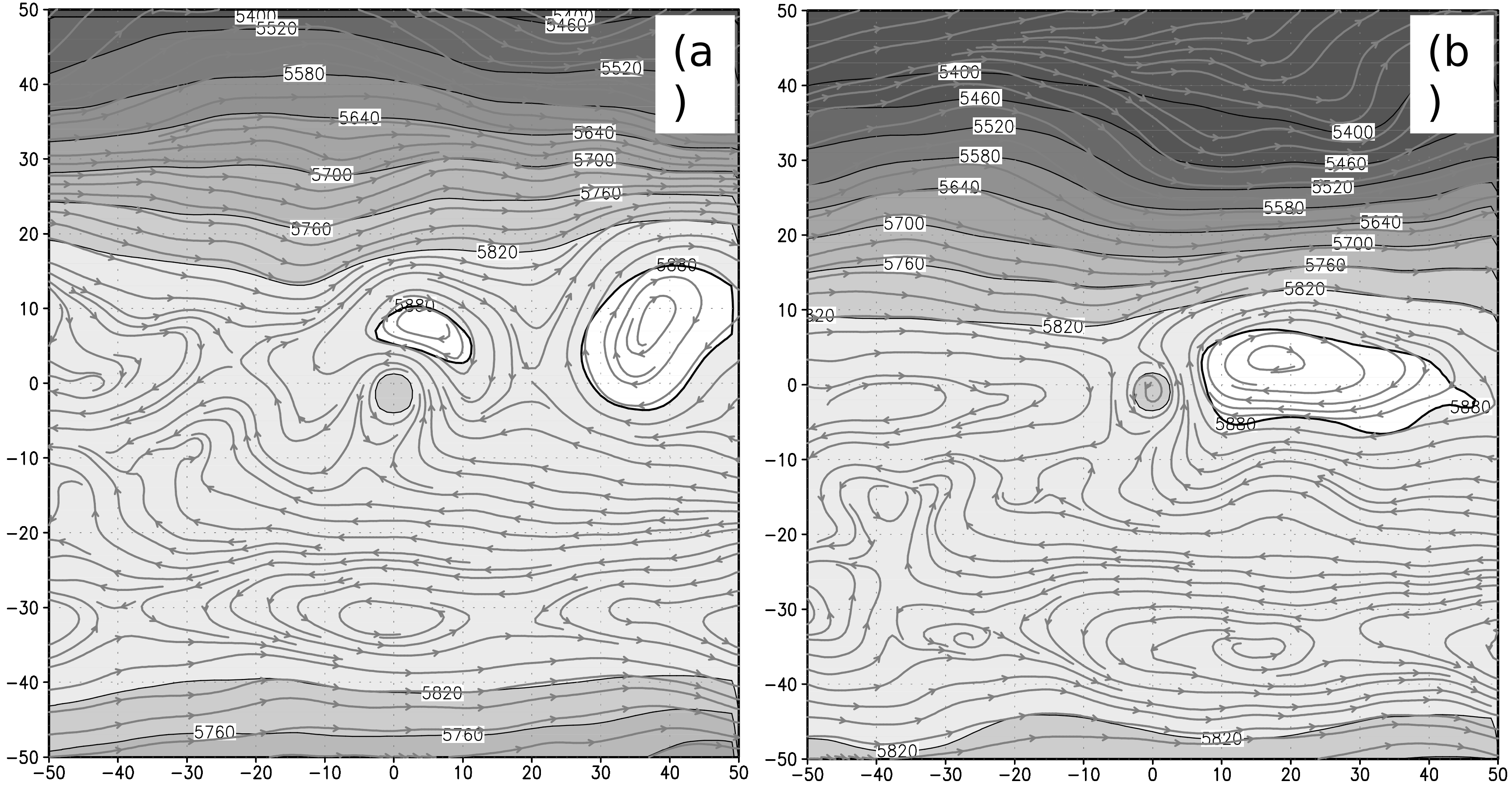
NEAR INFLOW GROUP | REMOTE INFLOW GROUP



– Maximum sensitivity near the storm before recurvature, but can be very remote (far upstream) during recurvature

PART I: STORM-CENTERED COMPOSITES

NEAR INFLOW GROUP REMOTE INFLOW GROUP



- Composite of background 500-hPa streamlines and height show strong anticyclone to the north in the near inflow group and stronger northward flow around the anticyclone to the east in the remote inflow group.

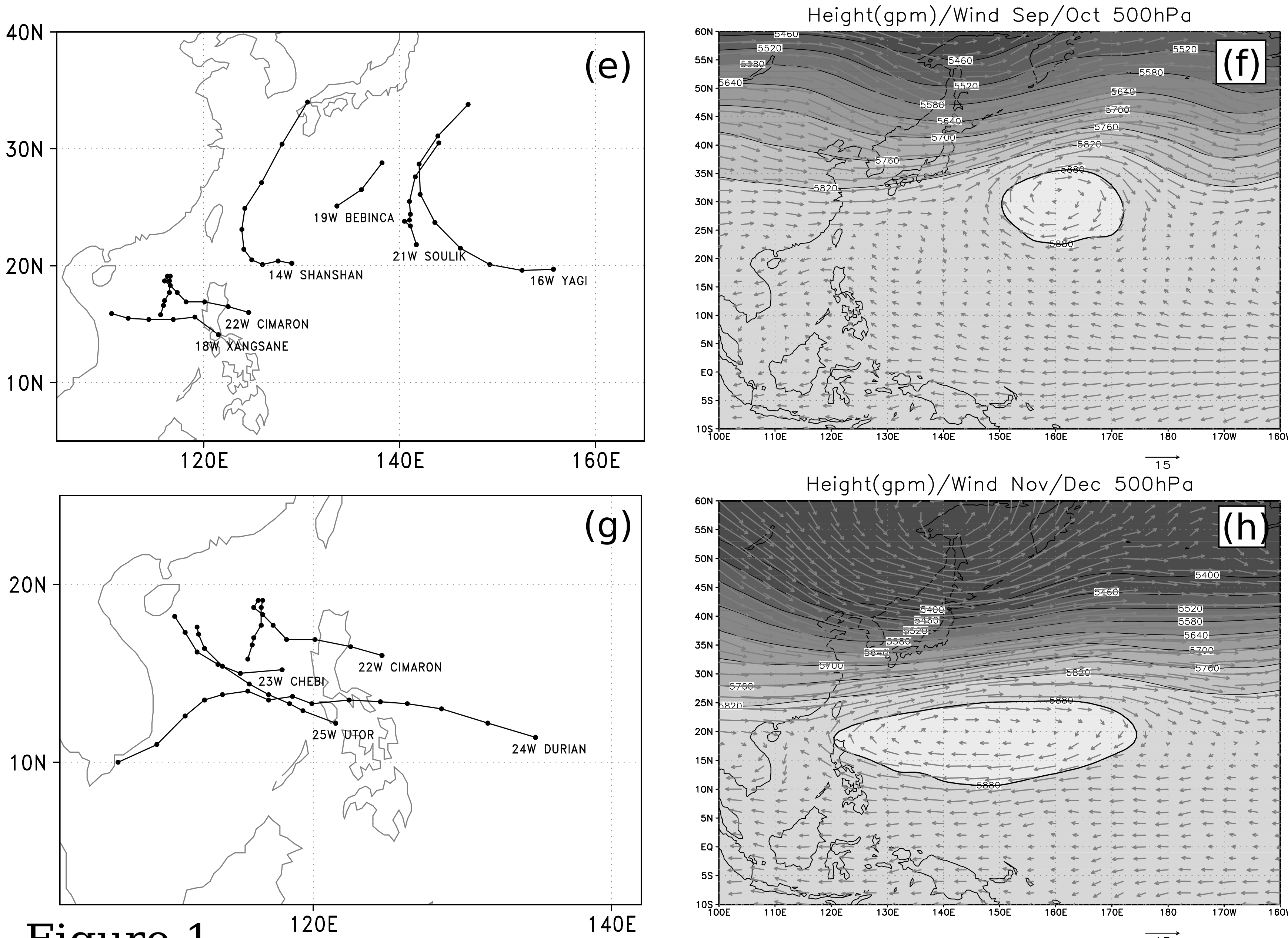
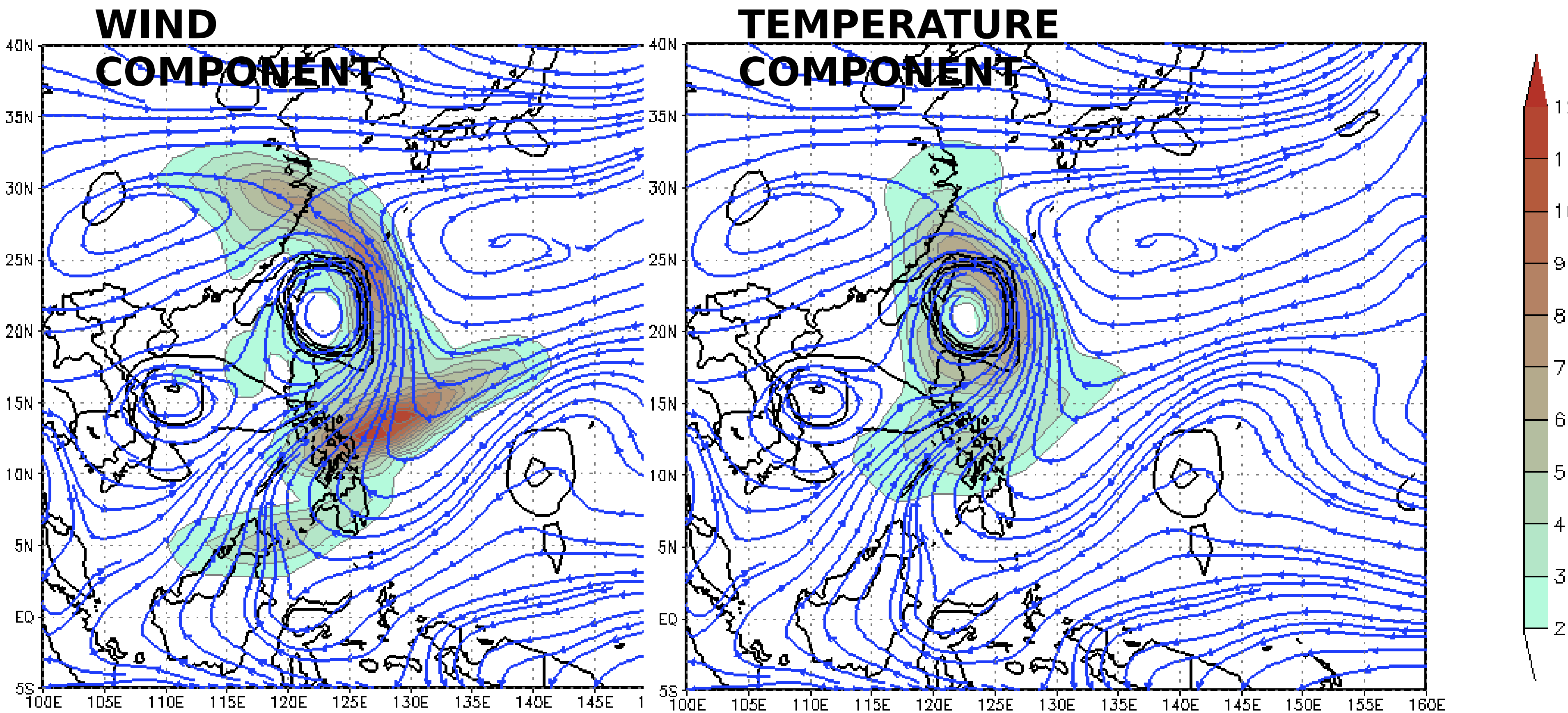


Figure 1 (continued)

NOGAPS SVs for Jangmi (2008092800)

Sensitivity dominated by wind field



Sensitivity to wind field max at 500-hPa

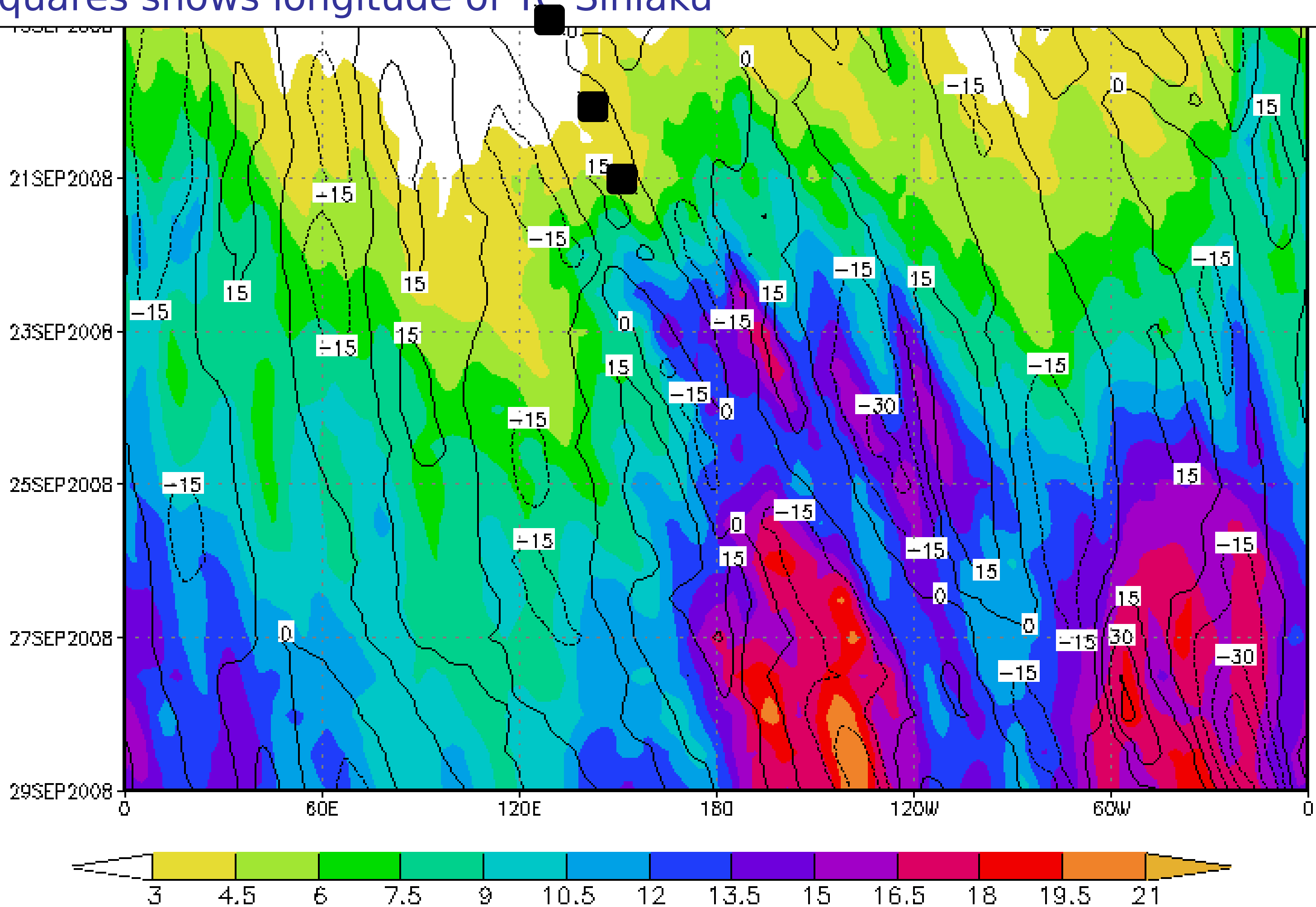
Sensitivity to temp field max in mid and upper troposphere.

NOGAPS Ensemble Products

NOGAPS ET Ensembles with Stochastic Convection (T119L30, 32-member + control, 240 h, once daily)

NOGAPS ET Ensemble 200-hPa V: black contours- control; shading – ens. spread, 35-60N

Squares shows longitude of TC Sinlaku



Time-longitude diagrams for depicting energy propagation, forecast uncertainty

Large ensemble spread downstream from Sinlaku indicating uncertainty in ET

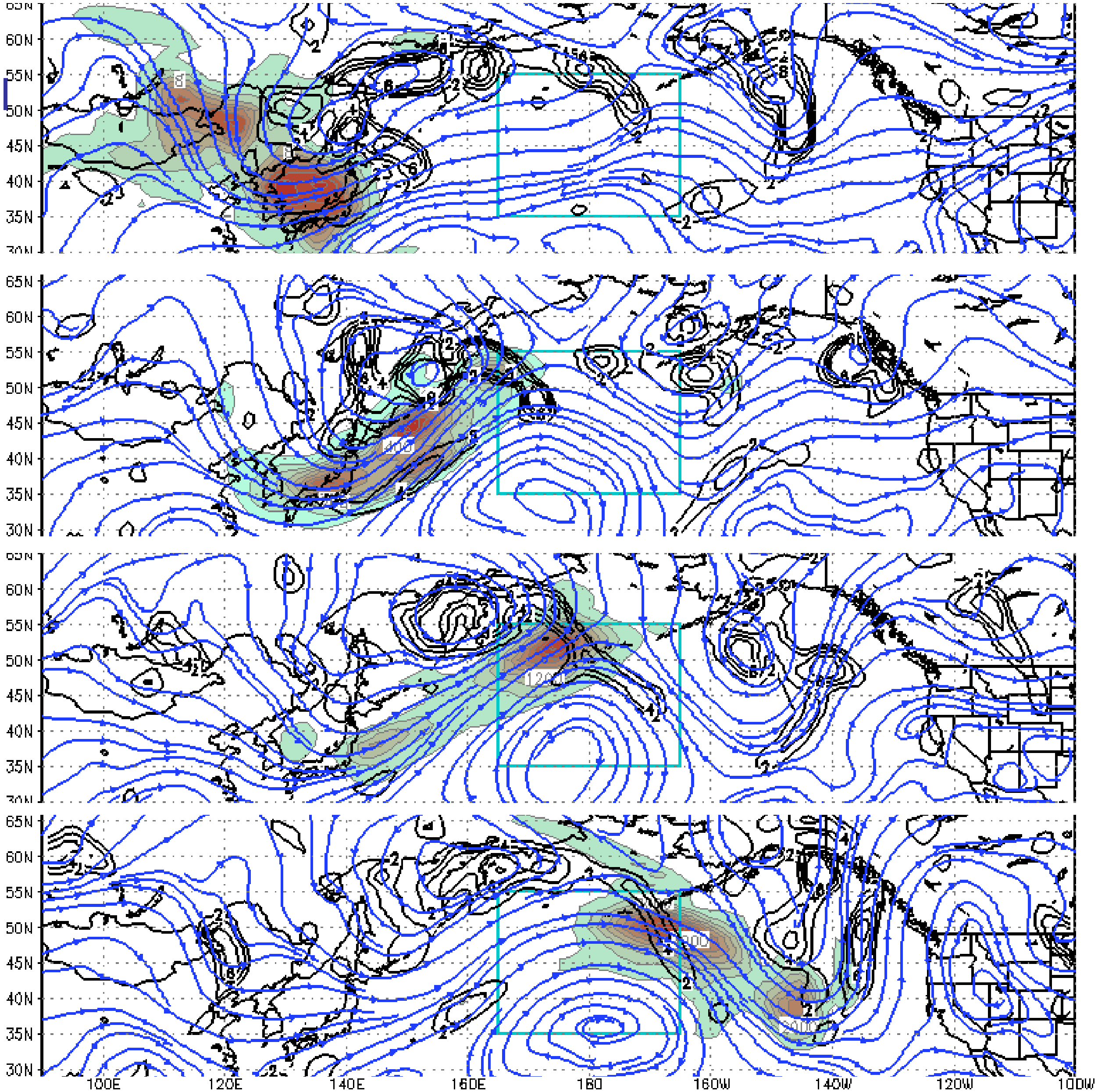
DOWNSTREAM PROPAGATION OF SIGNAL

Initial SVs

After 24h

After 48h

Final SVs



Evolution of NOGAPS North Pacific 72-h SVs from 2008092600

Illustrates rapid downstream propagation

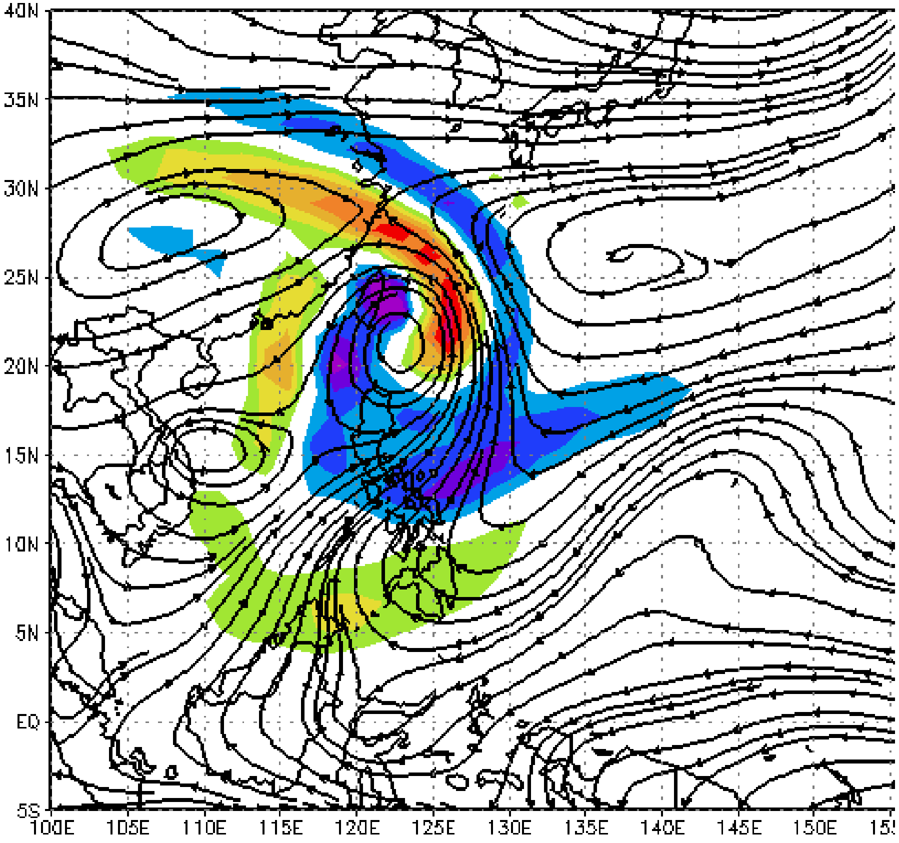
Useful for winter TPARC?

Try 96-h SVs?

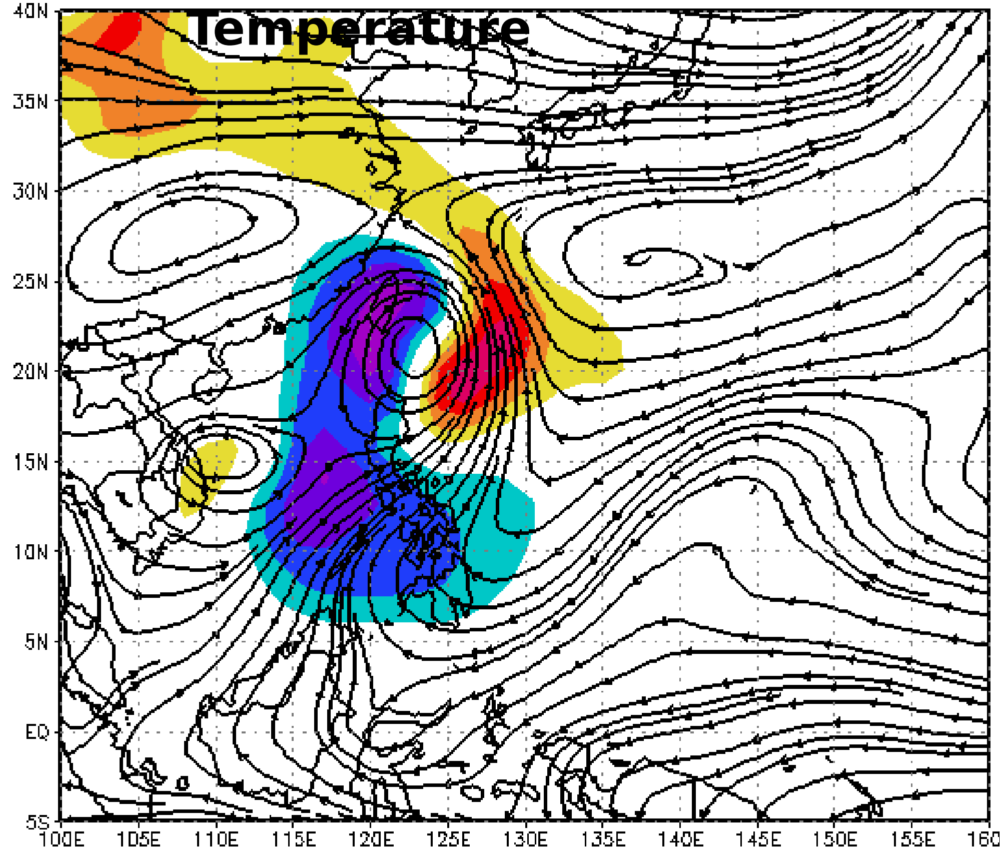
NOGAPS SVs for Jangmi (2008092800)

Sensitivity dominated by wind field

500-hPa Vorticity

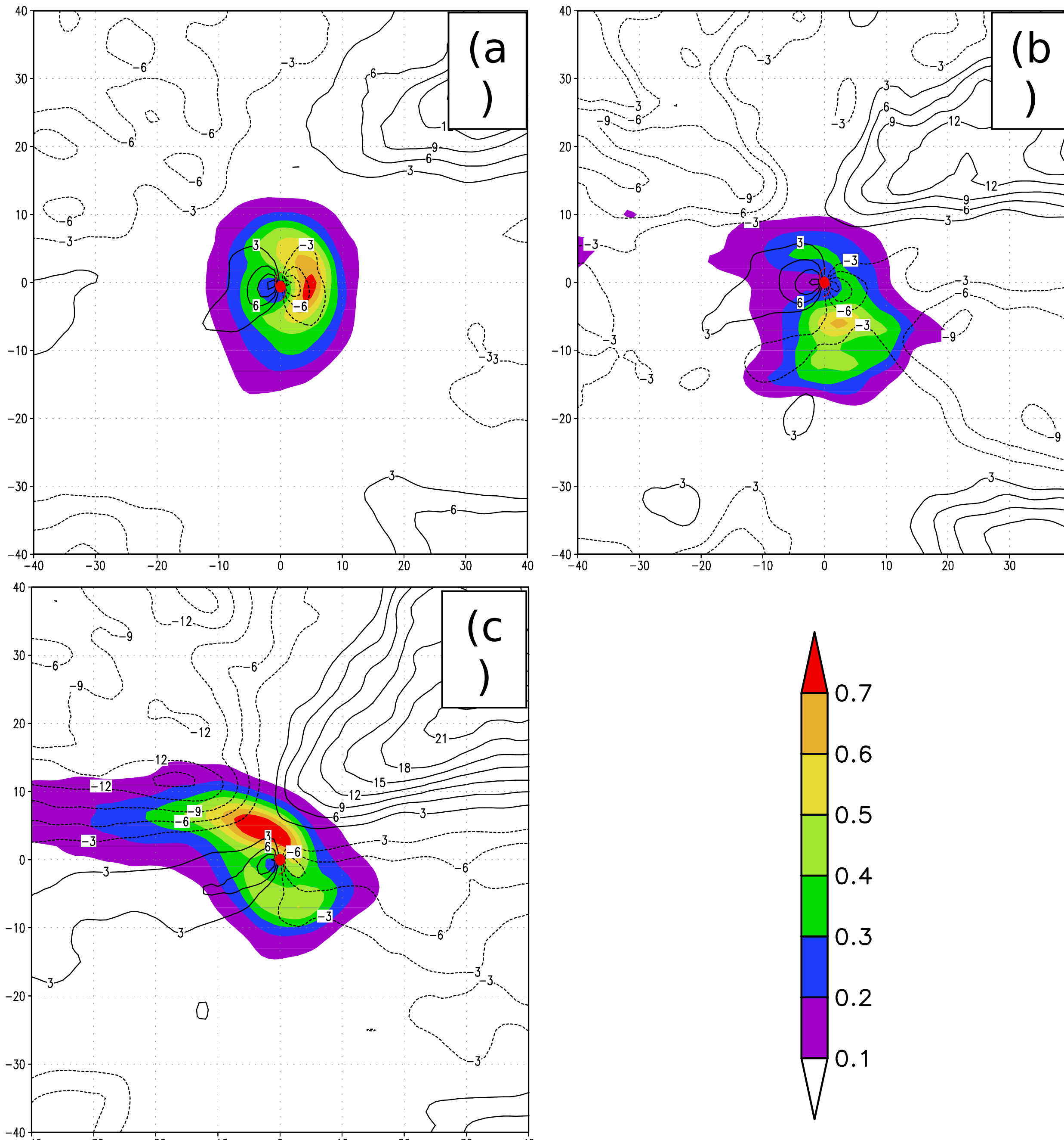


500-hPa Temperature

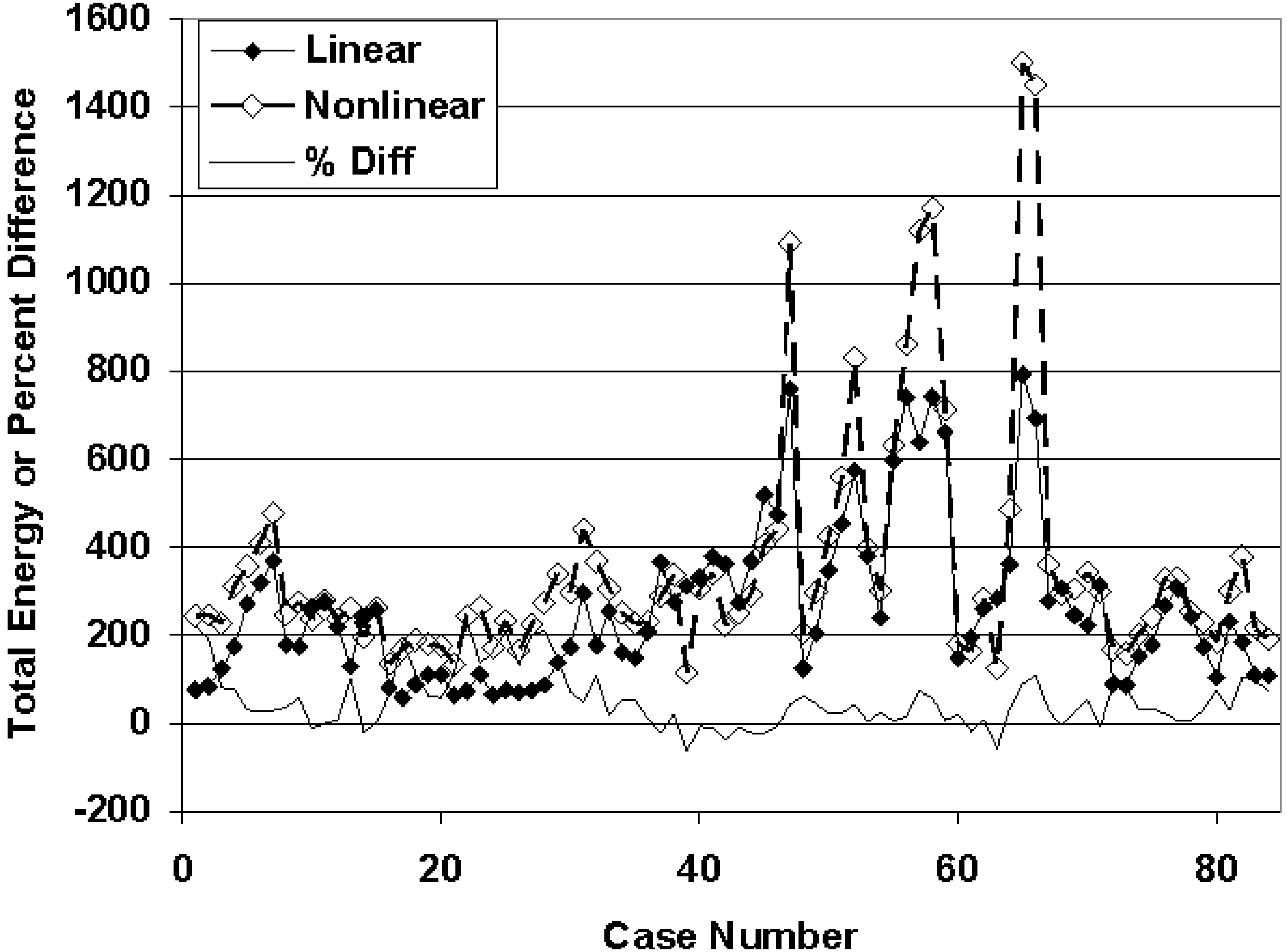


Elongated vorticity structures extend to southeast and northwest of storm

Temperature dipole about storm center

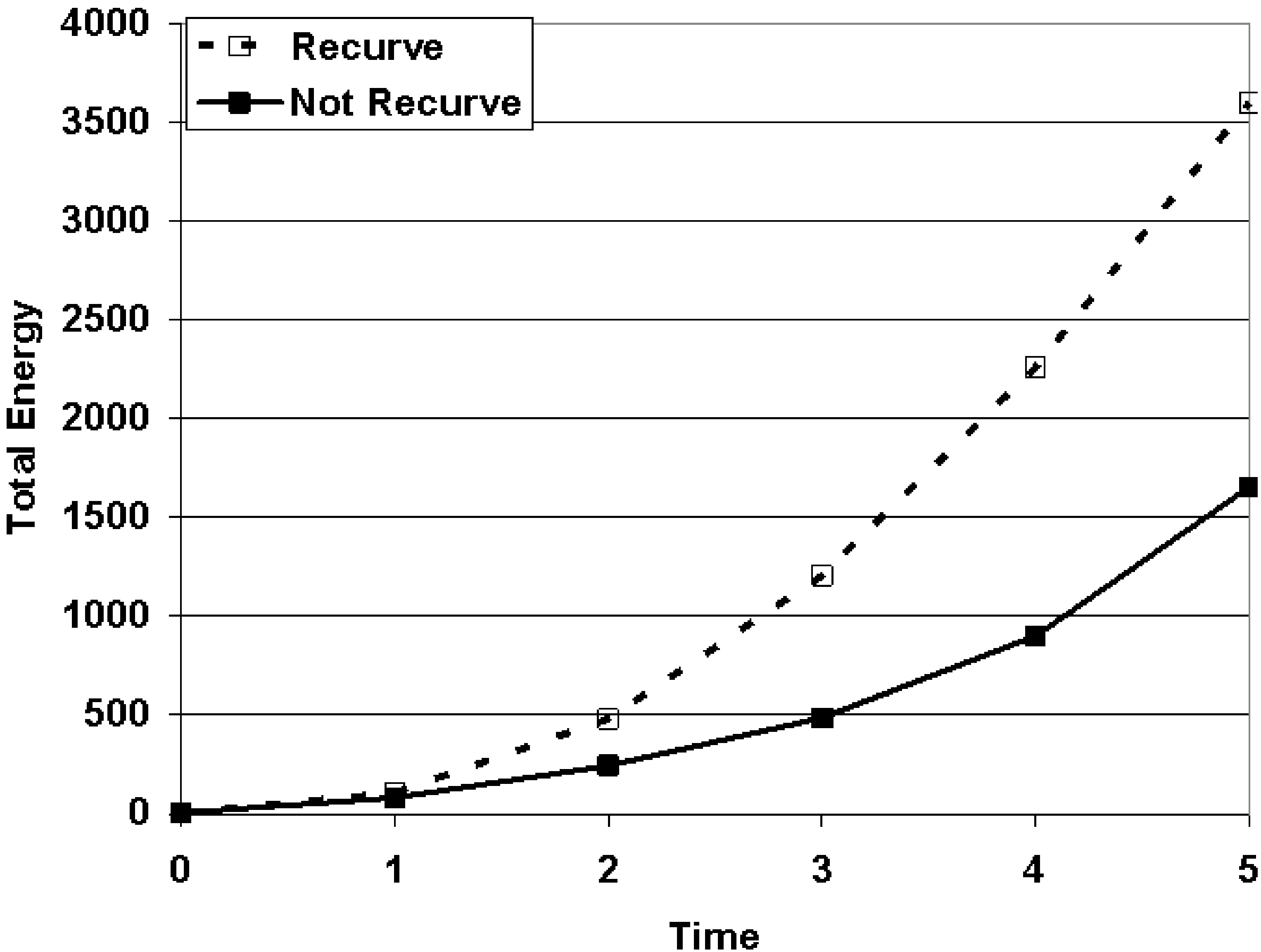

(a
)
(b
)
(c
)
0.7
0.6
0.5
0.4
0.3
0.2
0.1

RESULTS: PERTURBATION TOTAL ENERGY



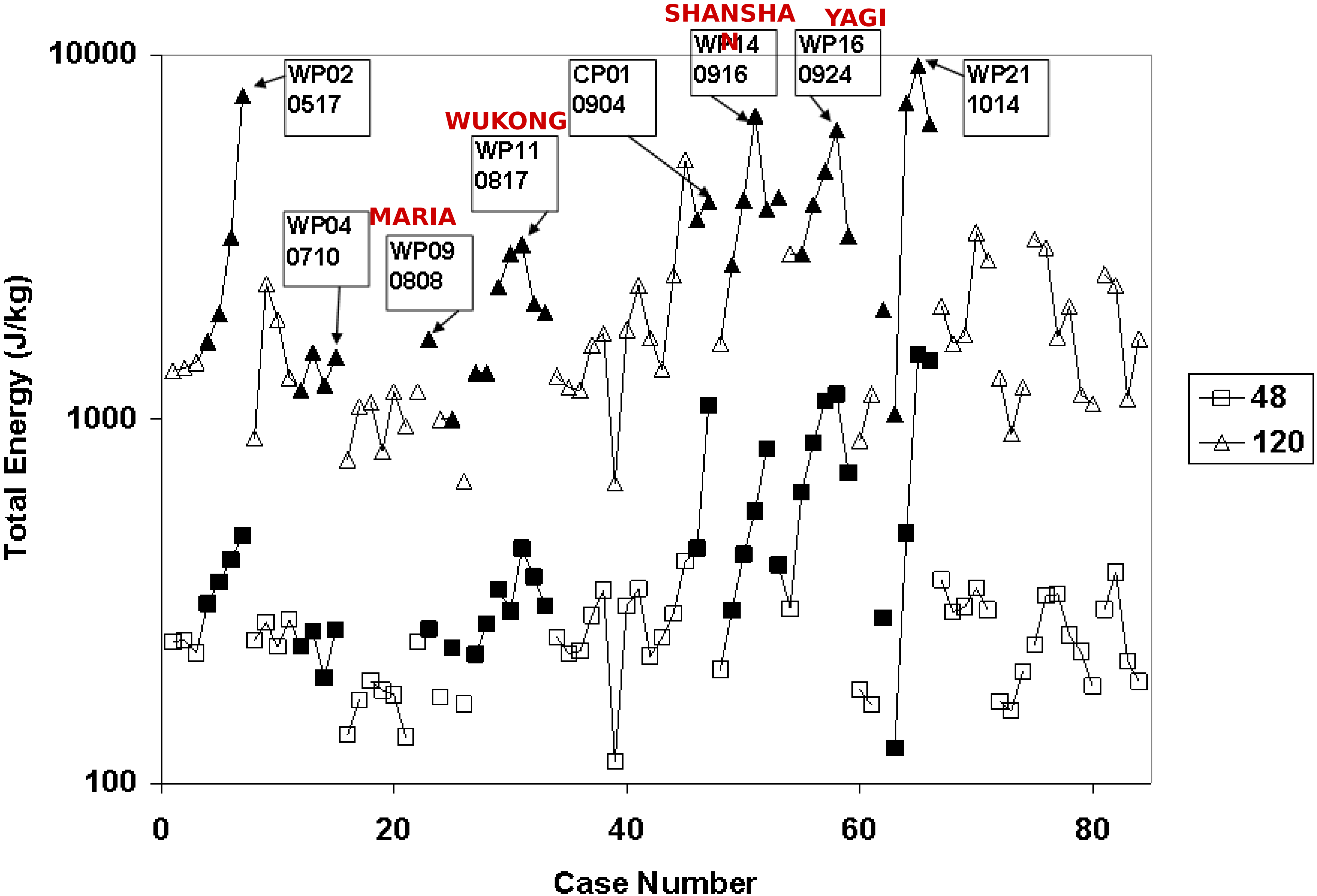
2-day linear and nonlinear perturbation growth similar (0.78 correlation). Nonlinear growth usually larger than linear growth.

RESULTS: PERTURBATION TOTAL ENERGY



On average, nonlinear perturbation growth significantly greater for recurving storms than for nonrecurving storms.

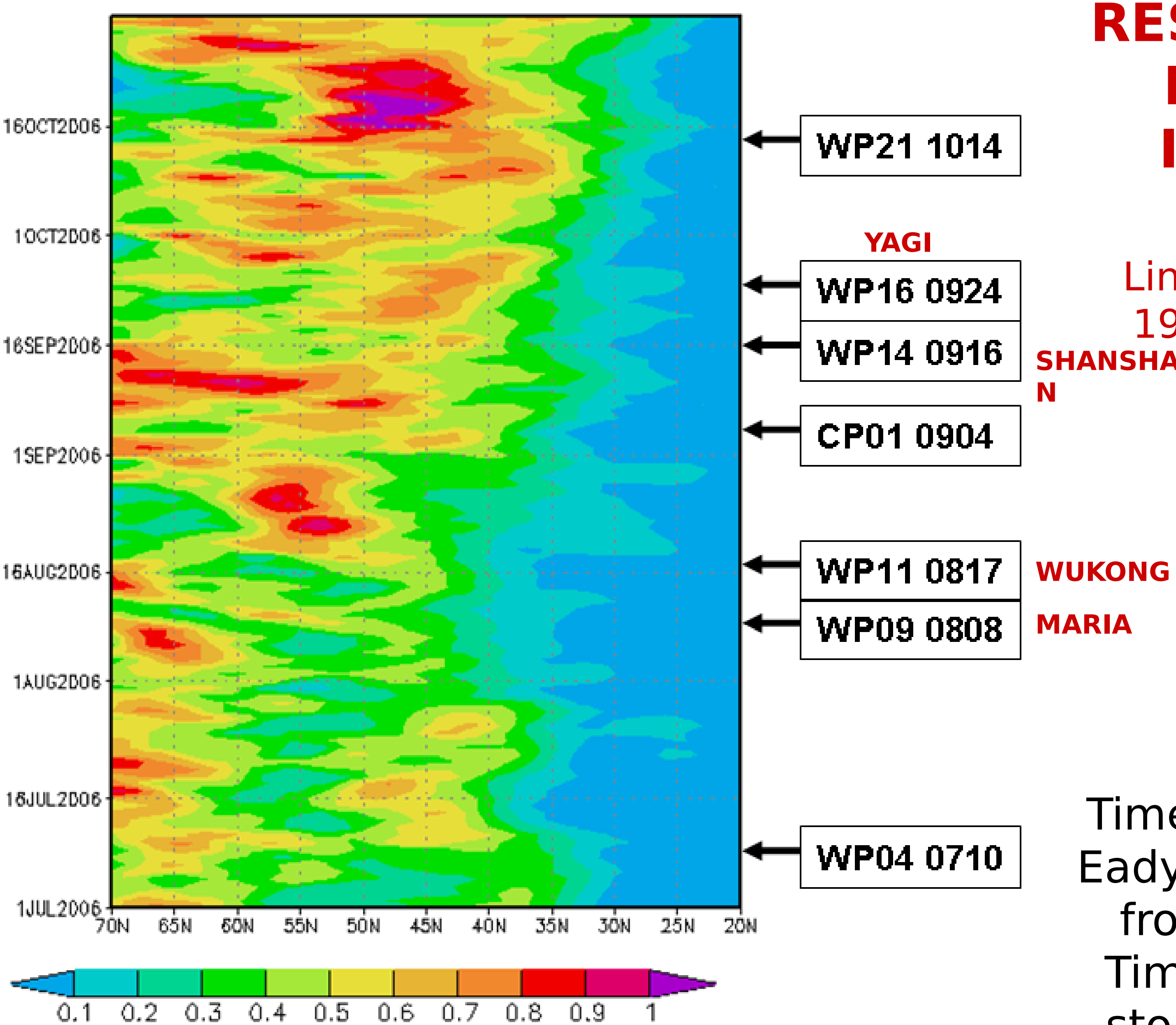
RESULTS: PERTURBATION TOTAL ENERGY



The strongest downstream impact is almost all from recurving storms (filled symbols). However, not all recurving storms have a strong impact.

RESULTS: Eady Baroclinic Instability Index

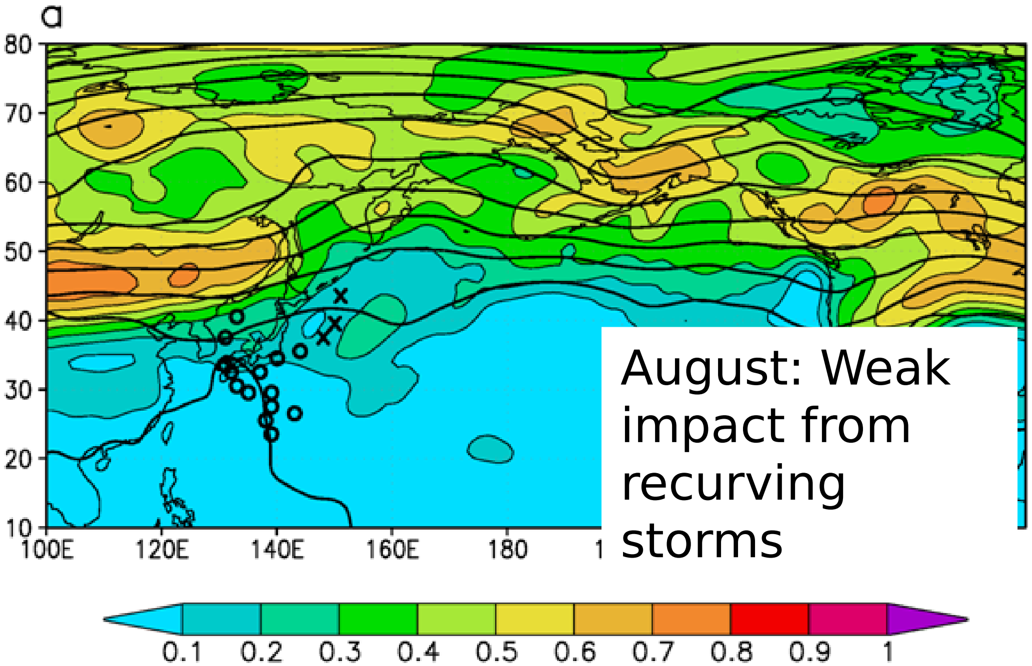
Lindzen and Farrell 1980 Hoskins and Valdes 1990



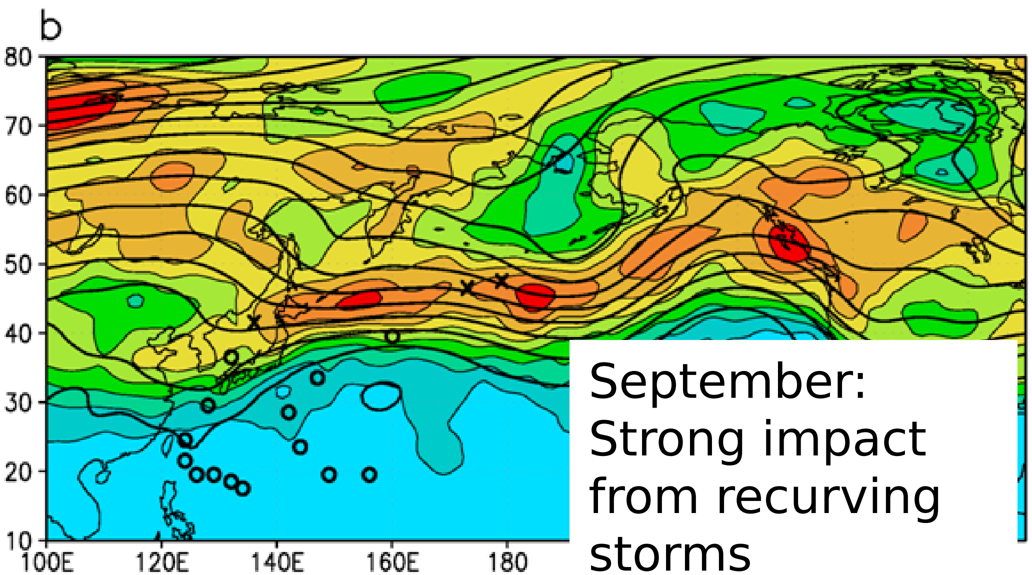
Time-latitude plot of Eady index averaged from 100E-160W. Times of recurving storms also noted.

Recurving storms with weak impact (WP11 and WP09) occur during relatively weak baroclinic instability.

RESULTS: Eady Index



August: Weak impact from recurving storms

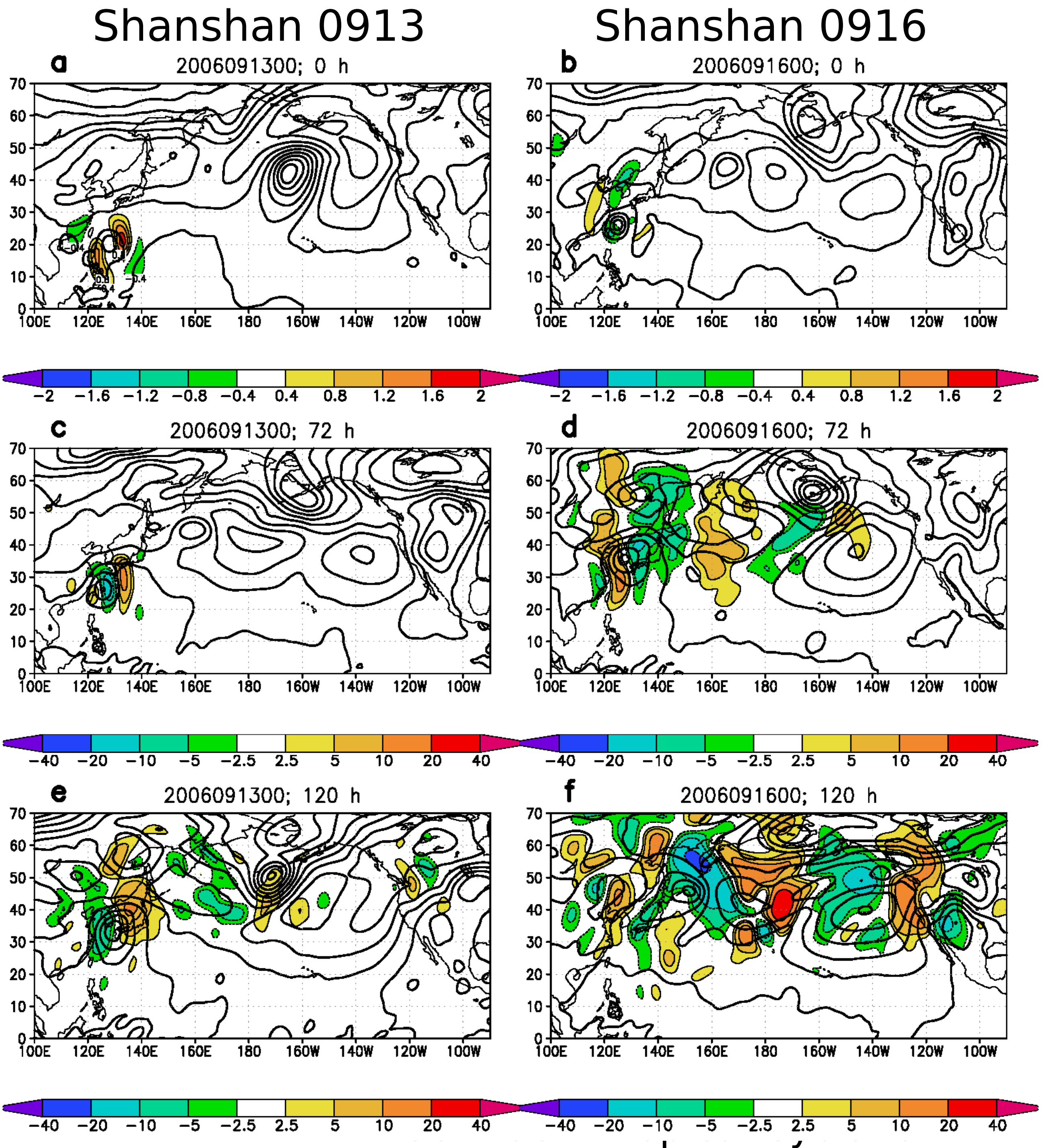


September: Strong impact from recurving storms

Stronger downstream impact for September storms.

Consistent with findings of stronger impact when downstream jet stronger (Riemer et al 2008), more unstable (Cardinali et al. 2007), and enter mid-latitudes in jet-entrance region (Klein et al. 2002)

Eady index (shaded) averaged for 6-21 August (top) and 11-27 September (bottom) with 500-hPa height (contour). Tracks of WP09 (Maria) and WP11 (Wukong) shown in top panel, and WP14 (Shanshan)



RESULTS: DOWNSTREAM IMPACTS

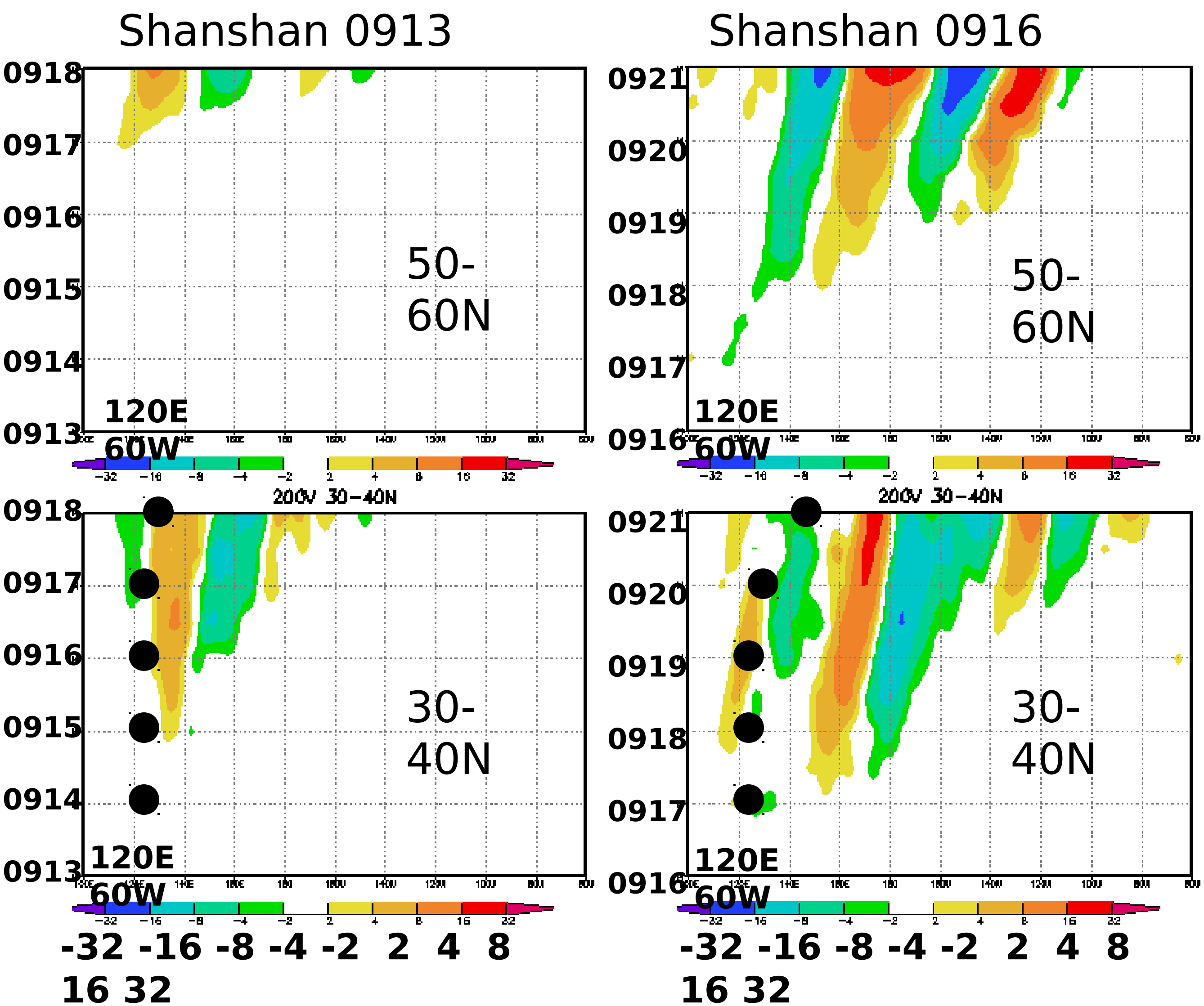
1) Make small SV-based perturbations to control analysis

2) Run nonlinear forecasts from control and perturbed analyses

3) 500-hPa V perturbation (shading) and control SLP

Downstream impacts are much larger during recurvature (0916), then before (0913)

RESULTS: DOWNSTREAM IMPACTS



Time-longitude diagrams of the perturbation 200-hPa V, averaged between 50-60N (top panels) and 30-40N (lower panels)

Eastward energy propagation much stronger during/after recurvature (0916)

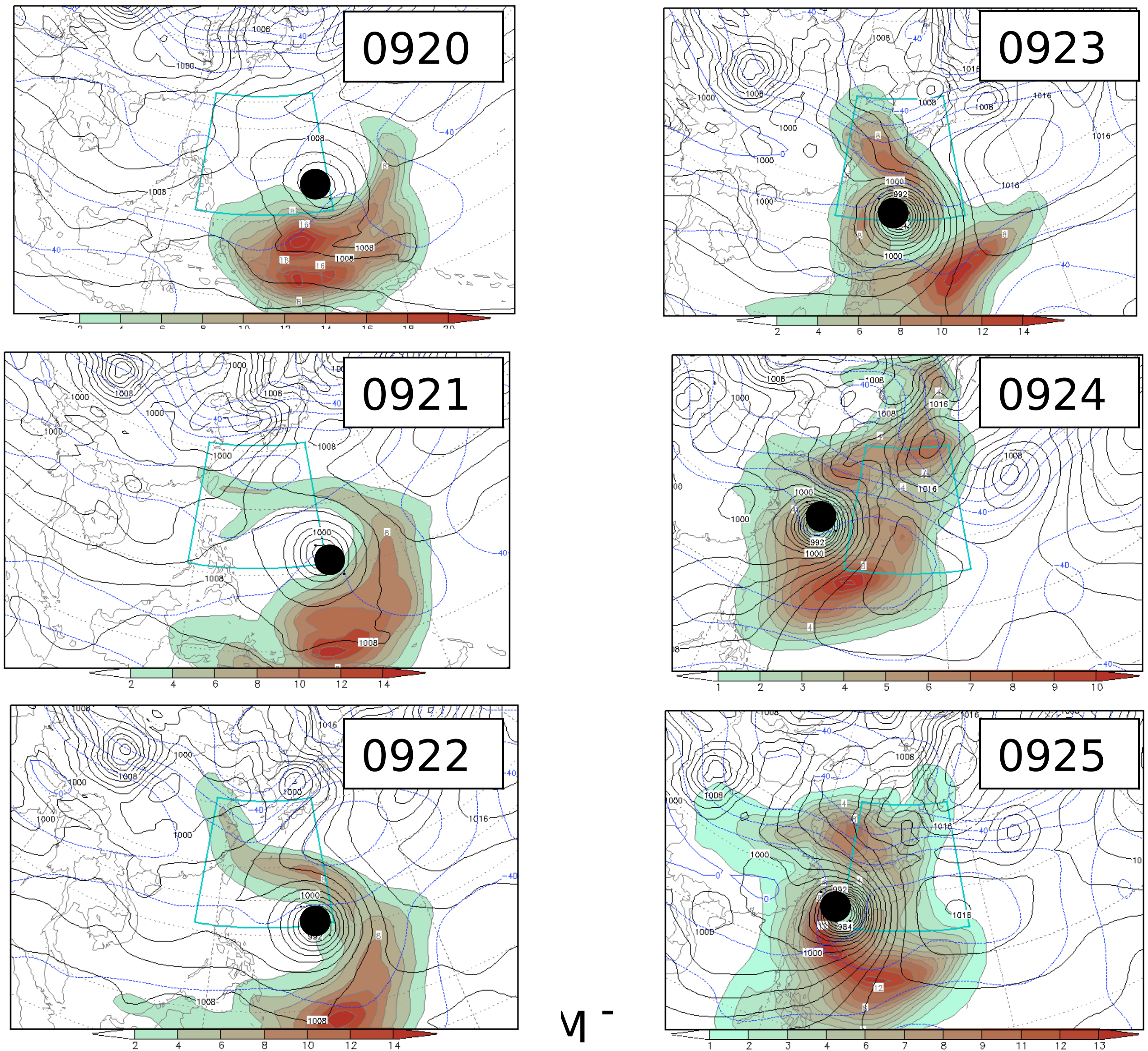
SUMMARY AND FUTURE WORK

- SV diagnostics indicate
    - Strong sensitivity often occurs far (4,000 km) upstream (over Asia) during recurvature
    - Near-storm KE dominant during early stages. Far-field PE becomes more important during recurvature*.
    - Nonlinear perturbation growth often larger than linear estimate
    - Small perturbations to storm can have very large downstream impact, particularly during/after recurvature

- SVs used for adaptive observing products during TPARC/TCS-08.
- Future work includes
    - Data denial experiments to examine impact of

RESULTS: CASE STUDY: MAN-YI (2007)

SV Total Energy during Man-Yi life cycle (shading). Analyzed SLP (black) and 200-hPa streamfunction (blue).



Man-Yi : Counter example

Synoptically “quiet” to north-west

Sensitivity to the north and northeast

Case-to-case variability significant

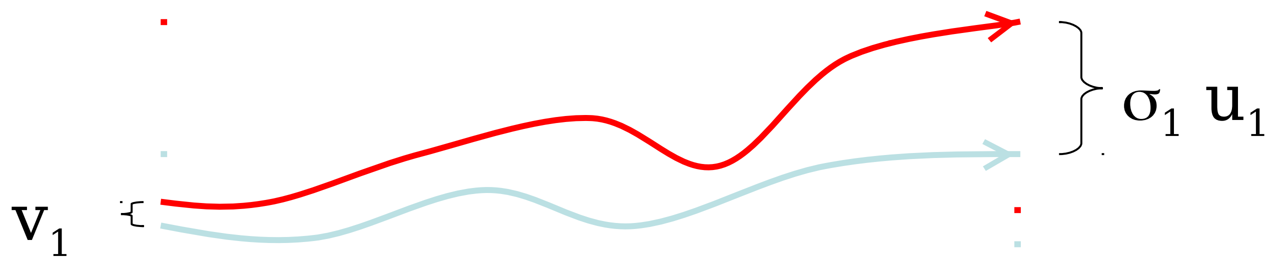
SINGULAR VECTOR DEFINITION

- Perform singular value decomposition to find SVs and singular values of tangent linear model **L**

$$\mathbf{L} = \mathbf{U}\,\Sigma\,\mathbf{V}^{\mathbf{T}}$$

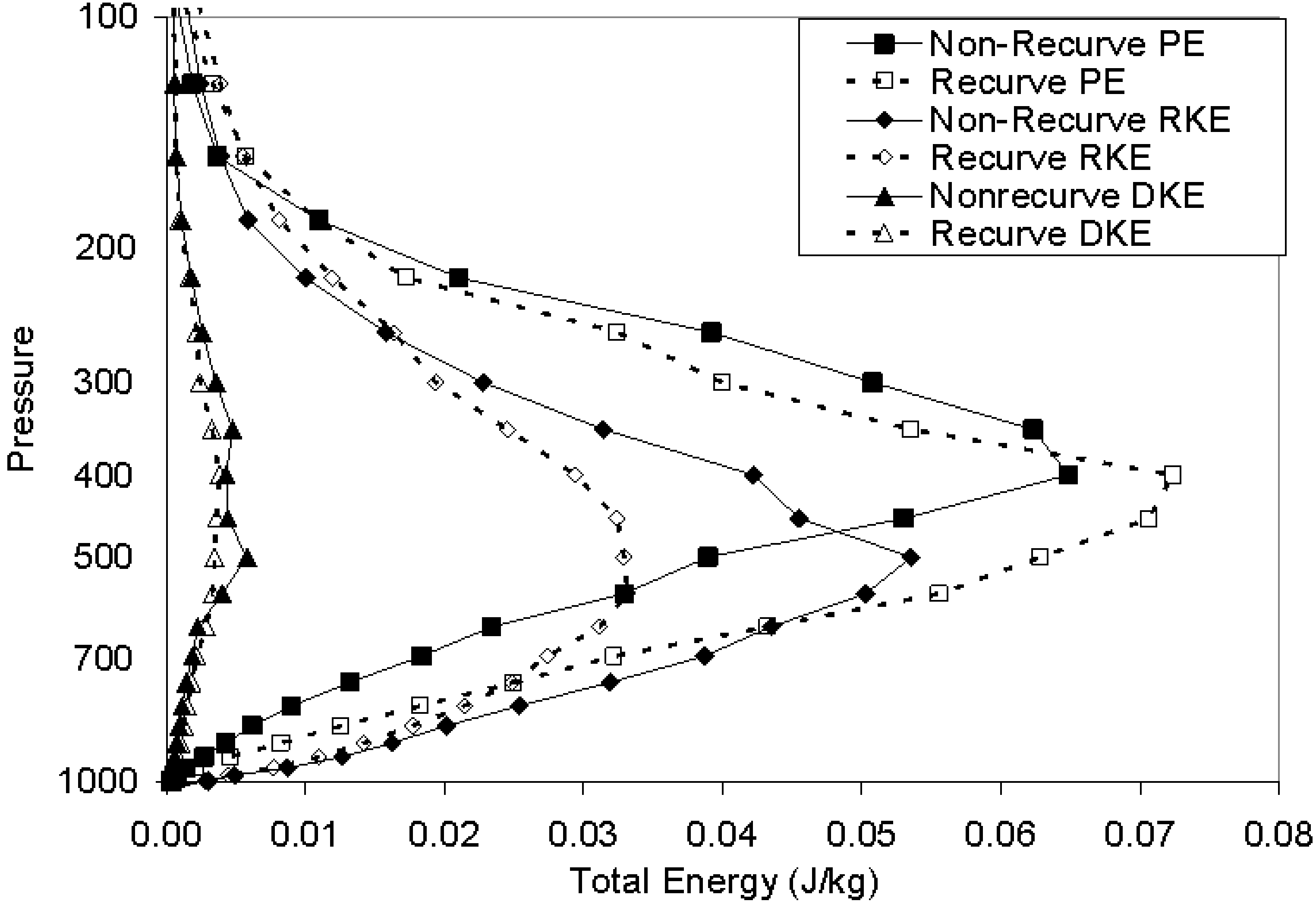
- The n^{th} initial-time SV, $\mathbf{v_n}$, evolves into the n^{th} final-time SV, $u_{\mathbf{n}}$, and amplifies the n^{th} singular value, σ_{n}.

$$\mathbf{L}\,\mathbf{v_n} = \sigma_n\, u_{\mathbf{n}}.$$



The leading SVs represent the fastest growing perturbations (in a linear sense) to a particular forecast trajectory. SVs can be used to examine the instability of the flow, as well as diagnose key initial perturbations that may grow rapidly into forecast errors.

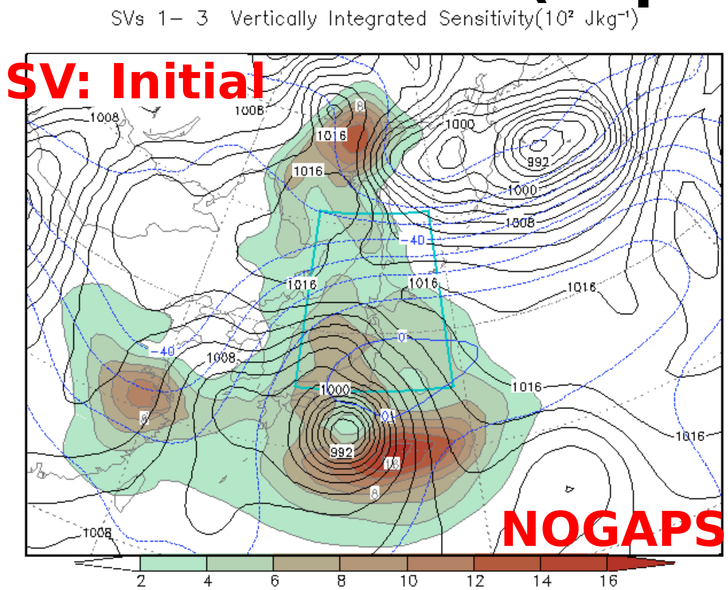
RESULTS: VERTICAL STRUCTURE

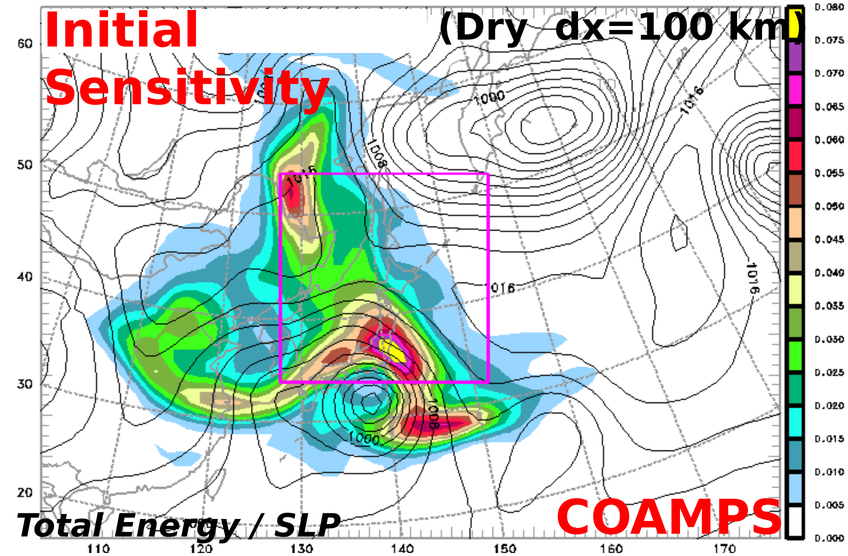


Recurving SVs have more PE (less RKE) than non-recurving SVs.

NRL TARGETING CAPABILITIES (NOGAPS AND COAMPS)

Fitow (Sep 6-8 2007) Mature Stage





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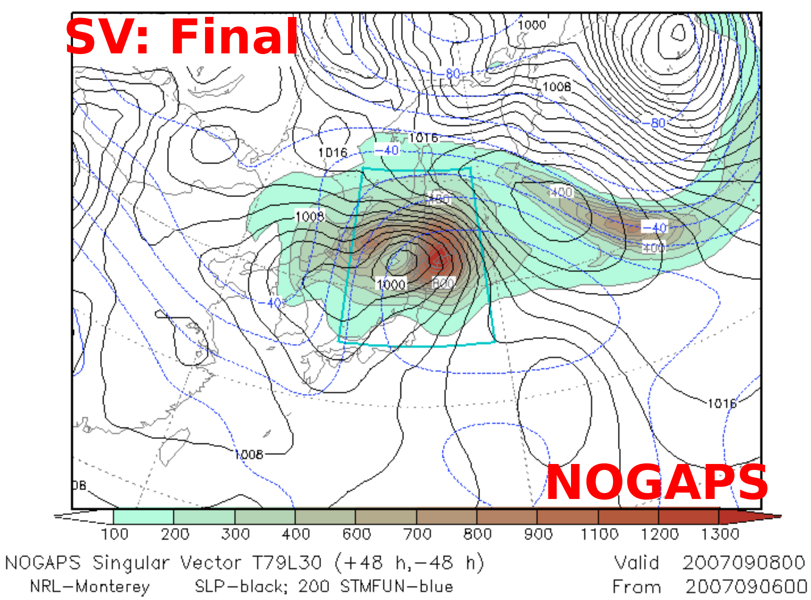

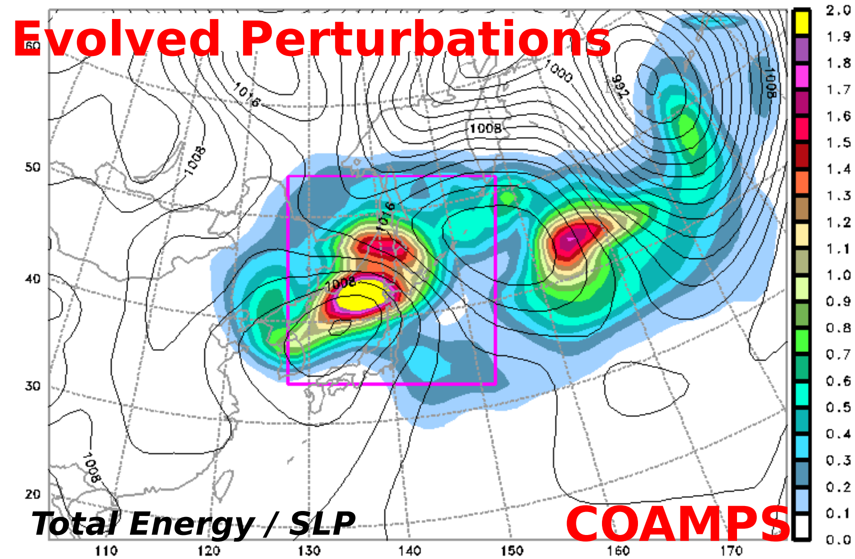

Doyle, Amerault, Reynolds